Technical Report GL-95-9
June 1995

US Army Corps of Engineers
Waterways Experiment Station

LEVEEMSU: Analysis Software for Levee Underseepage and Rehabilitation

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Prepared for Headquarters, U.S. Army Corps of Engineers

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Final report

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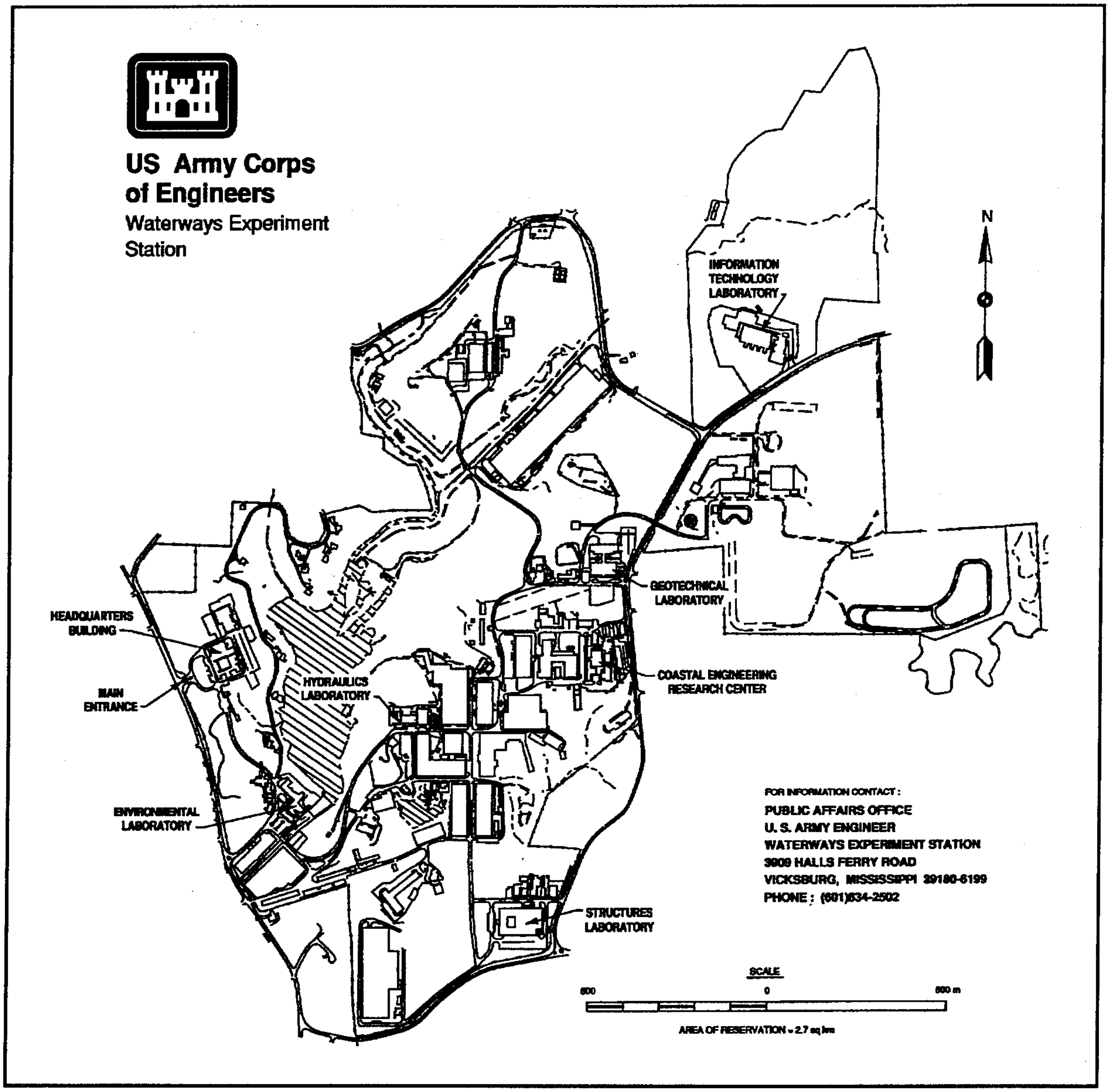
Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000



Waterways Experiment Station Cataloging-in-Publication Data

LEVEEMSU : analysis software for levee underseepage and rehabilitation / by M.A. Gabr ...
[et al.] ; prepared for U.S. Army Corps of Engineers.
119 p. : ill. ; 28 cm. — (Technical report ; GL-95-9)
Includes bibliographic references.
1. Levees — Evaluation — Computer programs. 2. Seepage — Computer programs. 3. Levees — Design and construction — Evaluation. I. Gabr, M. A. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Geotechnical Laboratory (U.S. Army Engineer Waterways Experiment Station) V. Title: Analysis software for levee underseepage and rehabilitation. VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-95-9.
TA7 W34 no.GL-95-9

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Preface

This report uses the computer software LEVEEMSU to describe analysis methodology for levee underseepage and rehabilitation. Information required for data input, calculation procedures, output, and graphics is presented. In addition, comprehensive results of case studies and parameter analysis utilizing LEVEEMSU are included. Several appendixes present example problems and input data files, calculations, graphics output, and summaries. This report extends and supplements U.S. Army Engineer Waterways Experiment Station (WES) Technical Report GL-89-13.

Funding for improvements of the program came from Headquarters, U.S. Army Corps of Engineers (HQUSACE), and from the Huntington District for the Magnolia, OH, levee case study. Funding from the HQUSACE was provided to make program improvements, corrections, modifications, and documentation under the Numerical Model Maintenance Program.

Work in this report was performed by Dr. M. A. Gabr of West Virginia University, Mr. Anthony L. Brizendine of Fairmont State College, and Mr. Hugh M. Taylor, Jr., Soils Mechanics Branch (SMB), Soils and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), WES. Mr. W. L. Hanks, SMB, provided automated drafting and editorial support. Appreciation is extended to Ms. Victoria L. Edwards, Airfields and Pavements Division, for typing and editing the report in WES format. Conversion to the Microsoft QuickBASIC (TM) language was performed by Mr. M. K. Sharp, Engineering Geophysics Branch, Earthquake Engineering and Geosciences Division, GL.

This work was performed under the direct supervision of Mr. William M. Myers, Chief, SMB. General supervision was provided by Dr. Don C. Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Director, GL.

During the preparation and publication of this report the Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
feet per minute	0.3048	meters per minute
gallons (U.S. liquid) per minute	0.000006309	cubic meter per second
miles (U.S. statute)	1.609347	kilometers

Summary

The computer program LEVEEMSU for analysis of levee underseepage is presented with comprehensive parameter studies and application to case histories. Analysis algorithms implemented in LEVEEMSU are based on numerical modeling of the flow domain and geometric conditions with approximate solutions obtained. Numerical idealization of the subsurface geologic conditions is achieved from two-layer or three-layer representation with a unit length. In the two-layer model, seepage flow is assumed to be horizontal in the substratum and vertical in the top blanket. The three-layer model is for situations where geological settings of the top blanket consist of interbedded layers of silt, sand, and clay. In these cases, the bottom zone of the top blanket may form a transition zone that is mostly silt to silty sand. Seepage flow for the three-layer model is assumed to be horizontal in the substratum, vertical and horizontal in the transition zone, and vertical in the top blanket. The program computes heads and gradients as function of horizontal location.

The analysis models implemented in LEVEEMSU are developed based on assumptions similar to those commonly followed in conventional steady-state seepage analysis. However, while traditional procedures required that profile geometry be uniform, LEVEEMSU allows for the analysis of profiles with irregular geometry and variable seepage properties. Therefore, program solutions should allow the user to match conventional analyses and further extend them to complex conditions.

With the program LEVEEMSU, levee underseepage analyses can be performed while the following analysis variables are considered:

a. Irregular finite and infinite geometry.

b. Variable blanket permeability.

c. Lines of relief wells.

d. Landside and riverside ditches and borrow pits.

In general, parameter studies with application to problems with ditches and relief wells indicated that the program exhibits consistent behavior.

LEVEEMSU runs on IBM compatible personal computers (PC) under the MS DOS (trademark or TM) operating system with CGA, EGA, or VGA graphics capabilities. The capacity of the program is determined by the size of the variables in the DIMENSION statements. Maximum number of nodes that can be generated in the current version is 300. Creation of the input file is relatively simple. The program features a graphic display of input and output data to aid in checking the input and interpreting the results. Description of the input file and the analysis variables is as follows:

<u>Example Data File:</u>	<u>Variable Names</u>
IRREGULAR FOUNDATION	TITLE1$
THREE LAYER-TEST PROBLEM	TITLE2$
0.200	KF
0.0002[1] 0.002[1]	KMVR[1] KMHR[1]
2 "CONST" .0002 175	NRIVSECS PERMFLAGR$ PERMRIV YRIV
0 0 70 80 90[1]	X(1), Y1(1), Y2(1), Y3(1), Y4(1)[1]
1150 0 70 80 90	"
0.0002[1] 0.002[1]	KMVR[1] KMHR[1]
2 "CONST" .0002	NLANDSECS PERMFLAGL PERMLAND
1800 0 70 80 90[1] 90	X(*), Y1(*), Y2(*), Y3(*), Y4(*)[1], YWATER(*)
5000 0 70 80 90 90	"
NO WELLS	WELLFLAG$

Magnolia Levee, located in Huntington District, and Sny Island Levee, located in Rock Island District, are selected as case studies to demonstrate the application of the two-layer and three-layer models, respectively. Results of the case studies emphasized the importance of accurate characterization of the foundation sublayers. The selected length of the top blanket riverside and landside significantly impacts the predicted gradients. Predictions of exit gradients and hydraulic heads reasonably matched measured data.

---

[1] Omit for two-layer model.

LEVEEMSU provides a convenient analysis tool that should allow designers to approximately model actual field conditions. However, flood protection is a complex system involving design, construction, maintenance, and performance evaluation of levees. The use of LEVEEMSU can provide flexibility in exploring the influence of varying key analysis parameters on the predicted results.

1 Introduction

Background

This report uses the computer program LEVEEMSU to describe analysis methodology for evaluation of levee underseepage. This version of the program includes two-layer and three-layer analyses models for levees with irregular foundation. The solution algorithm implemented in the program is based on the use of finite difference formulation to model the steady-state flow domain. Numerical idealization of the subsurface geologic conditions is accomplished with the top blanket and foundation (two-layer) or top blanket, middle layer, and foundation (three-layer) representations being assumed. Development, testing, and use of the program are presented and discussed. Case studies for the verification of the computer model are also presented.

Levees are earth structures constructed to provide flood protection during and after high-water events. While levees were originally utilized for the protection of agricultural land from floodwater, their use for flood protection of industrial, commercial, and residential facilities has been increasing over the past two decades. In situations where flood-control levees are constructed on pervious foundations, seepage beneath a given levee, or underseepage, during high water can result in failure. Such a failure can develop because of excessive uplift pressures, piping, and subsurface erosion. A review of underseepage analysis procedures was prepared by Wolff (1986). Wolff noted that the Corps analysis and design procedures require a high level of judgment to formulate geometric and geologic conditions. In particular, while actual soil profiles and topography are often irregular, current procedures only model horizontal topography with uniform thicknesses of the soil layers. The judgment required for this step can lead to different analyses results for the same project.

In general, most of the Corps criteria for design of levees were developed in the 1940's and 1950's. There has been an emerging concern that Corps procedures and criteria may be overly conservative in many cases and unconservative in others. Overconservative design may necessitate the implementation of costly control measures where they may not be needed. Unconservative design is usually evident through the failure to identify areas where sand boils and erosion may occur.

A Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Levee Underseepage Workshop was held at the U.S. Army Corps of Engineers, Waterways Experiment Station (WES), on 10 April 1984 to establish research needs related to levee underseepage control. Representatives from the Rock Island, St. Louis, Memphis, and Vicksburg Corps of Engineers Districts participated in the workshop. One research task identified was comparing predicted levee underseepage conditions to observed performance. Data collected in the past two decades on the performance of levees during major flood events can be used for this purpose.

Previous Studies

Investigation of potential levee underseepage was initiated in 1937 by the Mississippi River Commission (MRC) in response to problems caused by the 1927 flood. A study was carried out by WES in the 1940's to investigate causes of underseepage and sand boils along the lower Mississippi River levees. Possible methods of evaluating the quantity of underseepage, uplift pressure, and hydraulic gradients were developed. In addition, possible control measures have been identified and investigated. The developed procedures were based on closed-form solutions for differential equations of seepage flow presented by Bennett (1946).

Technical Memorandum (TM) 3-424 by U.S. Army Engineer Waterways Experiment Station (1956) documented the analysis of underseepage and design of control measures for the lower Mississippi Valley levees. The developed analysis procedure provided means for the evaluation of the residual head (h_o) at the levee toe on the landside. The general geology of a typical levee at the lower Mississippi Valley included a thin layer of low permeability soil, referred to as the top blanket, underlain by pervious soil, referred to as the foundation. The critical hydraulic gradient for levees in this area, designated as exit hydraulic gradient, was estimated by dividing h_o by the thickness of the top blanket. Parameters needed for the estimation of the exit hydraulic gradient included the riverside and landside water elevations, the levee geometry, and the geometrical and geological characterization of the subsurface stratum. It was assumed that underseepage control measures were needed or extended if the exit hydraulic gradient exceeded an allowable value (typically assumed to be 0.85).

In the same TM 3-424, a detailed discussion was presented on the surficial floodplain geology and its relationship to underseepage and occurrence of soil boils. Design and analyses procedures presented in TM 3-424 were summarized by Turnbull and Mansur (1961 a,b). Engineer Manual (EM) 1110-2-1913 for levees (Headquarters, Department of the Army 1978) included the design procedures presented in the TM 3-424.

Wolff (1974) and the U.S. Army Engineer District, St. Louis (1976) reviewed the performance of the Alton-to-Gale levee system, located along the middle Mississippi River, during the record flood of 1973. It was concluded

in the report by the St. Louis District that the use of the Corps procedure resulted in reliable design of the levee. However, several areas where the existing procedure proved deficient were identified. These areas included the inaccurate two-layer characterization of the subsurface profile and the inability to model levee bends at corners.

A comprehensive report summarizing data from 29 piezometer ranges and as many as 9 high-water periods was presented by Cunny (1980) for levees in the Rock Island District. In this study, Cunny implied that the probability of occurrence of boils increases in locations of geologic discontinuities.

Daniel (1985) reviewed Cunny's report and other Rock Island data. He observed that, although the analysis suggested initiation of boiling at gradient of about 0.85, boils were observed to occur at gradients range of 0.54 to 1.02. A similar observation was noted as early as 1952 and presented in TM 3-424. Recommendations by Daniels included, among others, the development of a relatively sophisticated computer program to replace the existing simplified method of analysis.

In cases where excessive exit gradients are predicted, remedial measures are designed and implemented. The most common remedial measures include pressure relief wells, landside seepage berms, and cutoffs beneath the levees. Muskat (1937) presented a design methodology for relief wells as a remedial measure for levees with critical hydraulic stability. Middlebrooks and Jervis (1947) adjusted Muskat's method to account for the partial penetration of the relief wells. Barron (1948) presented a procedure for analyzing fully penetrating relief wells with the assumption of leakage through the top blanket. A methodology was presented in Civil Works Engineer Bulletin 55-11 (Headquarters, Department of the Army 1955), whereby partially penetrating wells with leaky top blanket were modeled. EM 1110-2-1905 (Headquarters, Department of the Army 1963) provided design tables for finite lines of relief wells based on electrical analog model studies. The current Corps guidance for design and maintenance of relief wells is given in EM 1110-2-1914 (Headquarters, Department of the Army 1992).

Procedures for the design of seepage berms as a remedial measure were presented in TM 3-424. These procedures addressed situations where the berm permeability is equal to or less than the top blanket permeability. Barron (1947) presented a design methodology for impervious, semipervious, and pervious berms. Modification to this design methodology was later performed by Barron (1948), and a procedure by which short berms are designed such that boiling is allowed to develop some distance away from the levee toe was presented. The Cunny (1980) study of Rock Island levees concluded that existing criteria for design of berms to increase hydraulic stability are conservative. Required seepage berm widths based on observed data were smaller than those estimated using the existing criteria.

Research regarding the application of numerical methods to levee underseepage analysis was conducted by Wolff (1987). It was shown that the use

of special purpose computer programs had certain advantages over both traditional underseepage analysis procedures and general-purpose numerical seepage analysis programs. As previously noted, traditional procedures (U.S. Army Engineer Waterways Experiment Station 1956) required that subsurface stratum, ground and water elevations, etc., be modeled with uniform thicknesses and depths. It is often the case that these parameters assume different values in a given cross section.

While general-purpose seepage programs using, for example, the finite element method (e.g., Tracy 1973) can model such irregularities, they are often expensive to use and require relatively high degree of effort to model a problem and interpret the results. In addition, information from conventional field investigations and engineering characterization of the subsurface soils are usually not sufficient to synthesize input parameters for the finite element model. For example, performing a two-dimensional finite element analysis would require data on the anisotropic permeability behavior of the soil. Such data are usually not available from traditional testing programs for site characterizations.

The research by Wolff (1987) included the development of "preliminary" programs to demonstrate the feasibility of the use of simplified numerical approach for analysis of levees underseepage. Three FORTRAN codes were developed including: LEVEEIRR, to model irregular geometry; LEVEE3L, to model three-layer foundations; and LEVEECOR, to model corners or bends in levee alignment. The development of these programs was achieved using the finite difference method with a simplified representation of the flow domain. Wolff (1989) developed the computer program LEVEEMSU for analysis of levee underseepage as a modified version of LEVEEIRR described above. This program was developed using BASIC code and included a number of Input/Output (I/O) and graphic enhancements. Analyses and development presented in this report extend the capabilities of the analysis scheme implemented in LEVEEMSU to include cases with three-layer irregular foundations and investigate the applicability of the developed computer models.

Scope

This report includes design models for the analysis of levee underseepage using LEVEEMSU. This version of the program includes two-layer and three-layer analyses models and represents a second-generation version of LEVEEMSU described above. The program uses a finite difference scheme to analyze underseepage for two-dimensional levee cross sections having nonuniform geometry and properties. Thicknesses and elevations of soil layers, ground surface, and riverside and landside ponded water may vary in the horizontal direction. Top blanket permeabilities may be specified independently for each side of the levee. Permeabilities may be modeled as having constant values or may vary as a function of blanket thickness. Heads and gradients are calculated as function of horizontal location. The effects of

a line of relief wells can also be modeled. The program features a graphic display of input and output data to aid in checking the input and interpreting the results. The program is also applicable for analyzing and designing ditches, borrow pits, etc. The program can be run in an interactive mode or in a batch mode.

Description of the analysis models is presented in Chapter 2. Details of the program layout and structure are included in Chapter 3. Parameter study and analysis of two case histories are presented in Chapters 4 and 6, respectively. Chapter 5 includes information on the program limitations. Chapter 7 illustrates the application of the design methodology for remedial measures.

Description of input data files is presented in Appendix A. Details on running the program are described in Appendix B. Two example runs illustrating a two-layer case and a three-layer case are shown in Appendix C. Standard input data files are listed in Appendix D. Appendix E presents a hand calculation for verification of the two-layer model. Appendix F is the Notation which lists symbols and abbreviations.

2 Solution Techniques

Seepage Under Levees: Two-Layer Model

Subsurface conditions beneath levees in alluvial valleys are traditionally modeled as two horizontal soil layers: a semipervious top blanket or top stratum of clay, silt, or silty sand overlying a pervious substratum of sand. Figure 1 illustrates the idealization of a two-layer underseepage model. Underseepage analyses are performed to predict piezometric heads and gradients along the base of the landside top blanket as function of riverside and landside water levels. In general, flood conditions riverside of the levee induce downward flow through the riverside top blanket, lateral flow through the pervious substratum, and upward flow through the landside top blanket. Under certain conditions of geometry and soil properties, the upward gradient in the landside top blanket can be excessive. If upward gradients are excessive, safety against boiling and piping is of concern. In cases where excessive gradients are expected, control measures are designed. Control measures typically include seepage berms or relief wells, and analyses are performed to assess the effectiveness of proposed or existing control measures.

Solution methodology

A solution for the piezometric head beneath a semipervious top blanket adjacent to a dam or levee on a pervious substratum was proposed by Bennett (1946). Bennett assumed perfectly horizontal flow in the pervious substratum and perfectly vertical flow in the top blanket. In addition, Bennett's solution was based on the assumption of constant thicknesses and permeabilities of the blanket and substratum. The piezometric head at the base of the blanket and the upward gradient through the blanket can be directly calculated for a number of various boundary conditions using the equations presented by Bennett.

Analytical solutions have been widely published within the Corps of Engineers (U.S. Army Engineer Waterways Experiment Station 1956; Headquarters, Department of the Army 1978, 1986) and elsewhere (Turnbull and Mansur 1961a,b). Underseepage analysis by the Corps has traditionally utilized these analytical solutions.

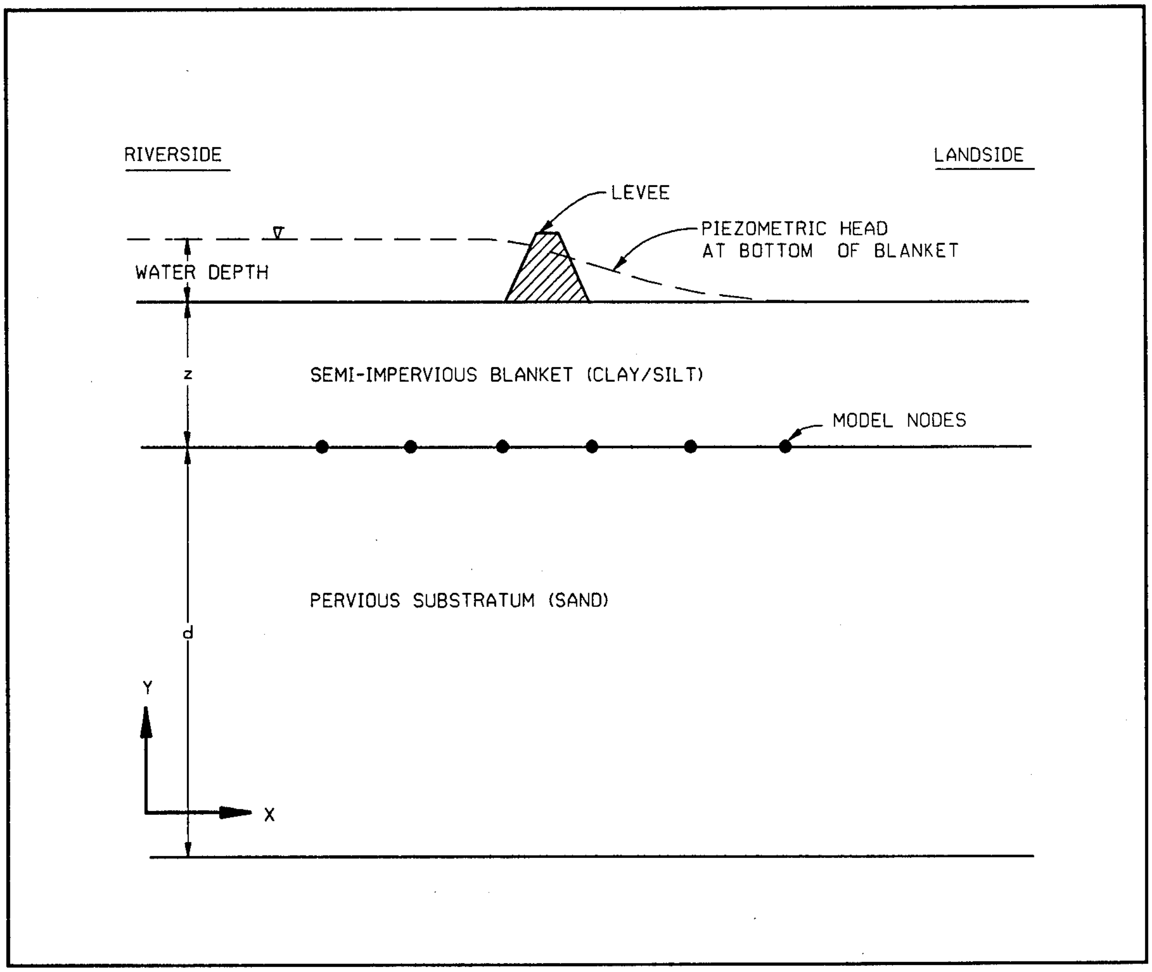


Figure 1. Two-layer underseepage model idealization

Analysis scheme

While analytical solutions are developed for cases with simple geometry and uniform soil properties, numerical methods can be used to solve Bennett's (1946) differential equation for irregular foundation geometry and nonuniform soil properties. With the use of numerical methods, analyses parameters can be assigned or interpolated at a number of points or nodes, and the differential equation is approximately represented at each node. Solution techniques have been presented by Wolff (1987) and are extended herein.

The cross section of the levee is modeled as a two-dimensional domain with a unit length. Seepage flow is assumed to be horizontal in the substratum and vertical in the top blanket; seepage through the levee is not considered. To obtain a one-dimensional numerical solution, consider a line of nodes along the interface between the substratum and the top blanket. The program user describes the foundation geometry using x and y coordinates along a number of vertical sections. The program generates a set of nodes and associated geometry information based on the user input. Dimensions and

properties are assumed to vary linearly between nodes. As the piezometric head in the substratum is implied to be constant along any vertical section, each node actually represents the entire thickness of the substratum at the location of the node.

Figure 2 illustrates conditions at a typical node. The node (J) is located at coordinates XX(J) and YY2(J). In the x direction, the node represents a length of substratum and blanket extending halfway to each adjacent node, XX(J-1) and XX(J+1). In the y direction, the node is associated with a substratum thickness D(J) = YY2(J) - YY1(J), a blanket thickness Z(J) = YY3(J) - YY2(J), and a landside water elevation YYWATER(J). The piezometric elevation at the node, PIEZEL(J), is calculated by the computer program.

Flow through a representative element of the foundation is lumped at the model nodes for analysis. As noted in Figure 2, continuity requires that flow at each node landside of the levee satisfy the following equation:

$$Q_{in} - Q_{out} - Q_{up} = 0 \tag{1}$$

where

Q_{in} = flow in the substratum toward the node

Q_{out} = flow in the substratum beyond the node

Q_{up} = flow or seepage through the top blanket in the vicinity of the node

On the riverside of the levee, the same equation is used, but Q_{up} assumes a negative value. Between the landside and riverside levee toes, Q_{up} is assumed to be zero.

Solution scheme

Based on Darcy's law, the quantity of flow can be expressed as follows:

$$Q = kiA \tag{2}$$

where

Q = quantity of flow

k = soil coefficient of permeability

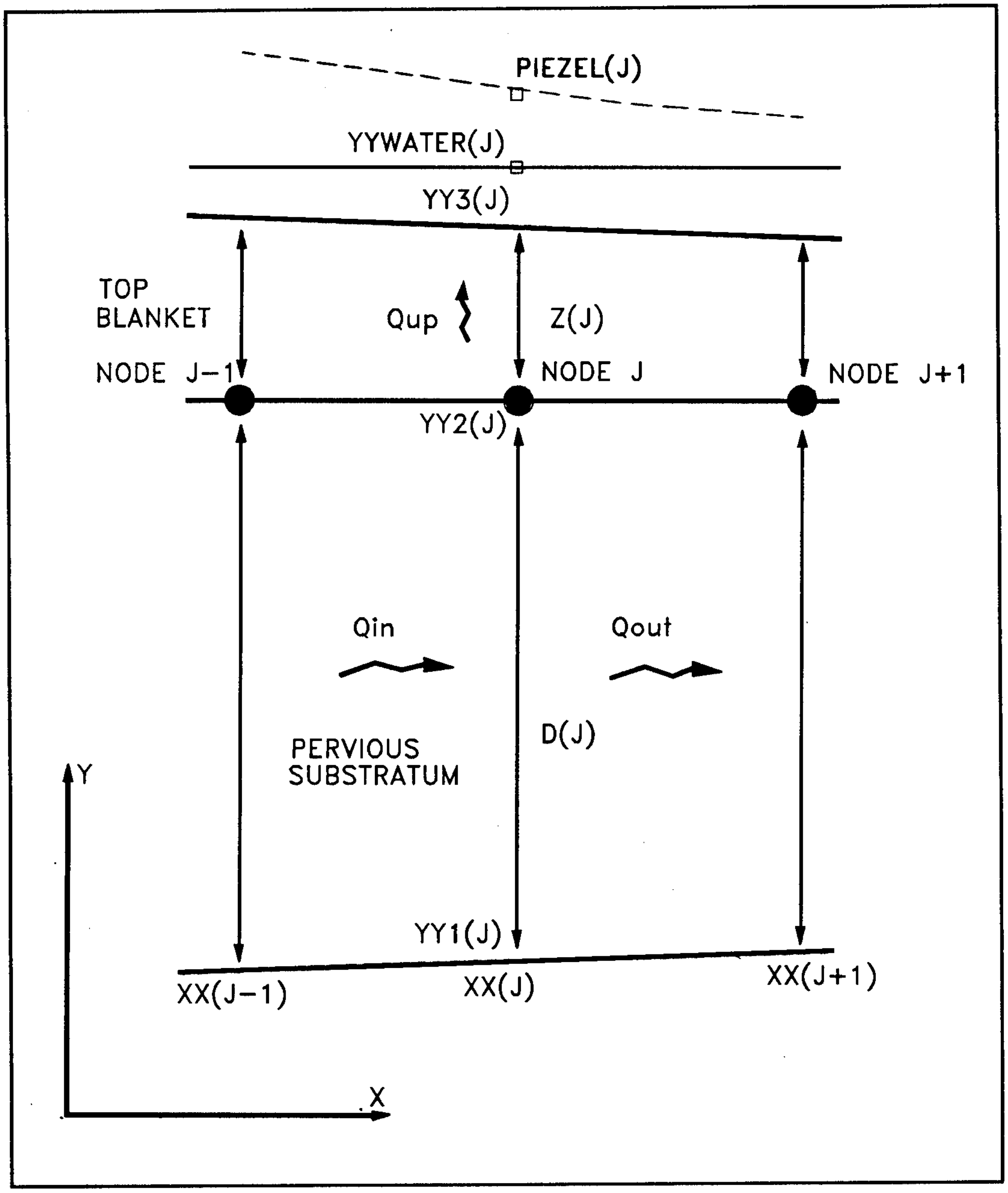


Figure 2. Two-layer underseepage model: geometry and finite difference approximation

i = hydraulic gradient

A = cross-section area normal to the flow

According to the finite difference method and Figure 2, the flow terms can be approximated numerically as follows:

$$Q_{in} = KF(J)\ [D(J) + D(J-1)]\frac{PIEZEL(J-1) - PIEZEL(J)}{2[XX(J)-XX(J-1)]} \tag{3}$$

$$Q_{out} = KF(J)\ [D(J+1) + D(J)]\frac{PIEZEL(J) - PIEZEL(J+1)}{2[XX(J+1)-XX(J)]} \tag{4}$$

$$Q_{up} = KB(J)\ [XX(J+1) + XX(J-1)]\frac{PIEZEL(J) - YYWATER(J)}{2Z(J)} \tag{5}$$

where

KF(J)	=	horizontal coefficient of permeability of the pervious substratum
D(J)	=	thickness of the pervious substratum at node J
PIEZEL(J)	=	elevation of the piezometric surface at node J
XX(J)	=	horizontal location of node J
KB(J)	=	vertical coefficient of permeability of the blanket at node J
YYWATER(J)	=	elevation of ponded water at node J
Z(J)	=	thickness of the top blanket at node J

Substitute the flow Equations 2 through 5 into the continuity Equation 1; then the piezometric elevation at any node J, PIEZEL(J), can be expressed as:

$$PIEZEL(J) = \frac{PIEZEL(J-1)*C1(J)+PIEZEL(J+1)*C2(J)+YYWATER(J)}{C1(J)+C2(J)+C3(J)} \tag{6}$$

where

$$C1(J) = \frac{(KF)*[D(J)+D(J-1)]}{2[XX(J)-XX(J-1)]} \tag{7}$$

$$C2(J) = \frac{(KF)*[D(J+1)+D(J)]}{2[XX(J+1)-XX(J)]} \tag{8}$$

$$C3(J) = \frac{(KB)*[XX(J+1)-XX(J-1)]}{2Z(J)} \tag{9}$$

Use an iterative technique to obtain an estimate for the piezometric head at node locations to solve Equation 6.

Seepage Under Levees: Three-Layer Model

In many practical situations, subsurface conditions beneath levees should be modeled from three-layer rather than two-layer characterization. Such situations arise in geological settings where the top blanket consists of interbedded layers of silt, sand, and clay. In these cases, the bottom zone of the top blanket may form a transition zone that is mostly silt to silty sand. Usually, such a zone may have a permeability value that falls in-between the relatively low permeability of the blanket and high permeability of the foundation. For these geological settings, a three-layer system is more representative especially in cases where relief wells are implemented as remedial measures. The three-layer model consists of the traditionally modeled semipervious top blanket or top stratum of clay, an intermediate or middle layer of silt or silty sand, and a pervious substratum of sand. Figure 3 schematically illustrates the idealization of a three-layer model.

Use the three-layer idealization to model flow such that flood conditions riverside of the levee induce downward flow through the riverside top blanket. Vertical and lateral flow is assumed to occur through the middle layer, and horizontal flow is assumed through the pervious foundation. Similar flow vectors are assumed for the landside with an upward flow through the top blanket. As discussed for the two-layer model and under certain conditions of geometry and soil properties, the upward gradient in the landside top blanket can be excessive. Excessive upward gradients cause boiling and piping that may jeopardize the safety of the levee. With the three-layer model, under-seepage analyses are performed to predict the piezometric head along the base of the landside top blanket and the base of the middle layer. Gradients as functions of riverside and landside water levels are estimated. In cases where calculations indicate that excessive gradients will develop, control measures including seepage berms or relief wells can be analyzed with the three-layer model. In addition, analyses may be performed to assess the effectiveness of proposed or existing control measures.

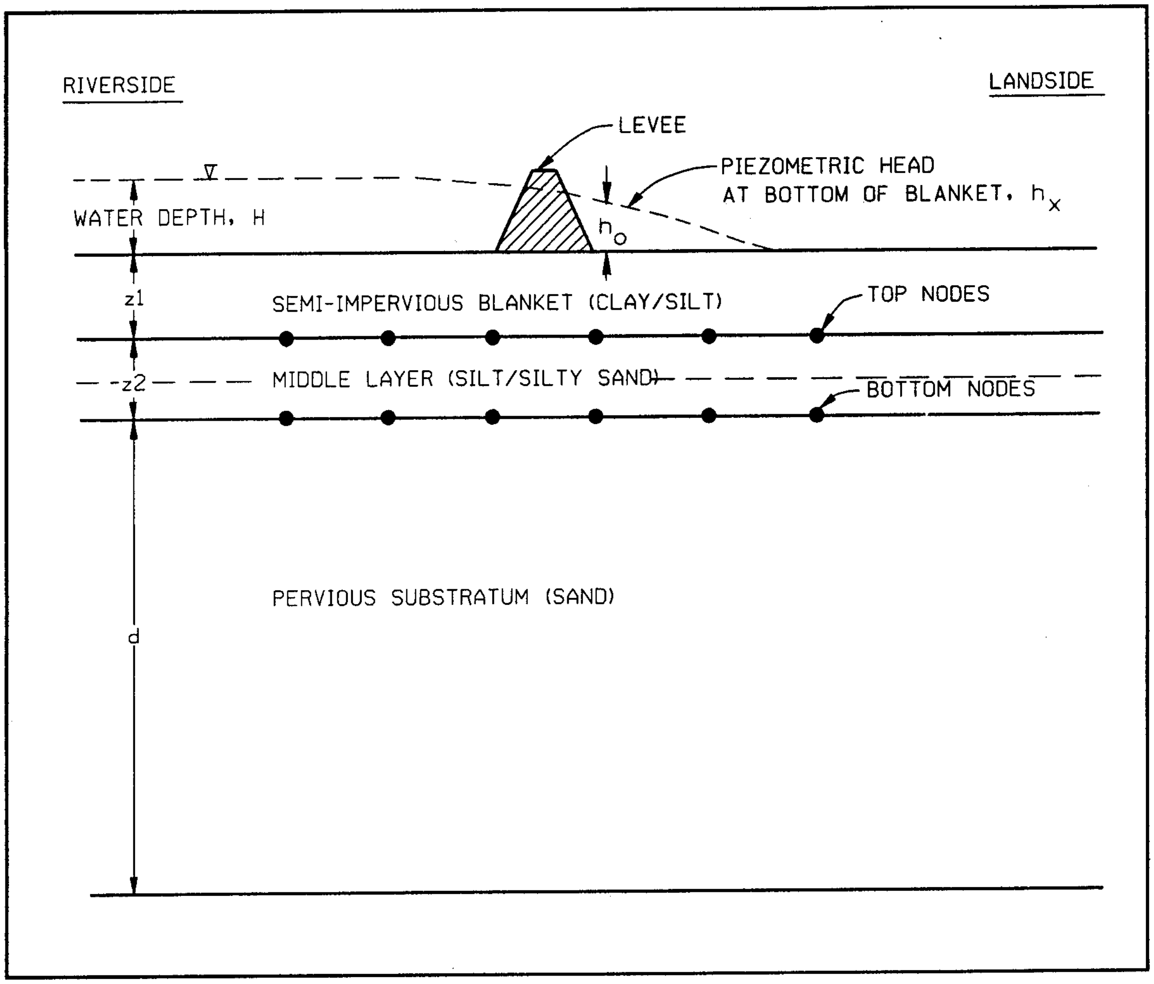


Figure 3. Three-layer underseepage model: domain idealization

Solution methodology

No analytical or closed form solutions are available for the three-layer idealization. In the LEVEEMSU computer program, the finite difference method with simplified assumptions is used to determine the solution numerically through the idealization of the flow domain. The solution is obtained for the piezometric heads and gradients beneath the semipervious top blanket and at the interface between the middle layer and the foundation layer.

Analysis scheme

The governing continuity equation for the three-layer model is developed using mass balance concept. The cross section of the levee is modeled as a two-dimensional domain with unit length. As mentioned earlier, seepage flow is assumed to be horizontal in the foundation substratum, horizontal and vertical in the middle layer, and vertical in the top blanket. To obtain one-dimensional numerical solution, consider two lines of nodes along the interface between the foundation and the middle layer and the middle layer and the

blanket. To describe domain geometry, use x and y coordinates along a number of vertical sections. The program generates a set of nodes and associated geometry information based on the input data. Dimensions and properties are assumed to vary linearly between nodes. Similar to the two-layer model each node in the three-layer model represents the entire thickness of the substratum at that node. The piezometric head in the foundation substratum is implied to be constant along any vertical section. Irregular foundation geometry and nonuniform soil properties can be analyzed through the specification of appropriate values at the different vertical sections.

The solution algorithm is based on the assumption that the middle layer can be divided into two equal parts with flow in the top half lumped into the top nodes and flow in the bottom half lumped into the bottom node. Figure 4 illustrates the model conditions at representative nodes. Two sets of nodes are located at the x-coordinate XX(J) with corresponding y-coordinates of YY1(3), YY2(J), YY3(J), and YY4(3). In the x direction, each node represents a length of foundation substratum, middle layer, and blanket, extending halfway to adjacent nodes at coordinates XX(J-1) and XX(J+1). In the y direction, the bottom nodes are associated with a substratum thickness D(J) = YY2(J) - YY1(J) and the thickness of the bottom half of the middle layer, YY3(J)-YY2(J)/2. The top nodes are associated with a blanket thickness Z(J) = YY3(J) - YY2(J), the thickness of the top half of the middle layer, and a landside water elevation YYWATER(J). The piezometric elevations at the top and bottom nodes are calculated by the program.

In general, the quantity of flow at each node can be expressed using Equation 2. As noted in Figure 4, continuity equations can be developed for the top and bottom nodes as follows:

a. *Top nodes.* Based on mass balance and continuity rules, flow in and out of each node must be equal. On the landside of the levee, the continuity equation can be written as:

$$Q_{in2top} + Q_{belowtop} - Q_{out2top} - Q_{uptop} = 0 \qquad (10)$$

where

Q_{in2top}	=	horizontal flow in the top half of the middle layer from the left adjacent node
$Q_{belowtop}$	=	vertical flow in the middle layer from the adjacent bottom node
$Q_{out2top}$	=	horizontal flow in the top half of the middle layer to the right adjacent node
Q_{uptop}	=	vertical flow in the top blanket

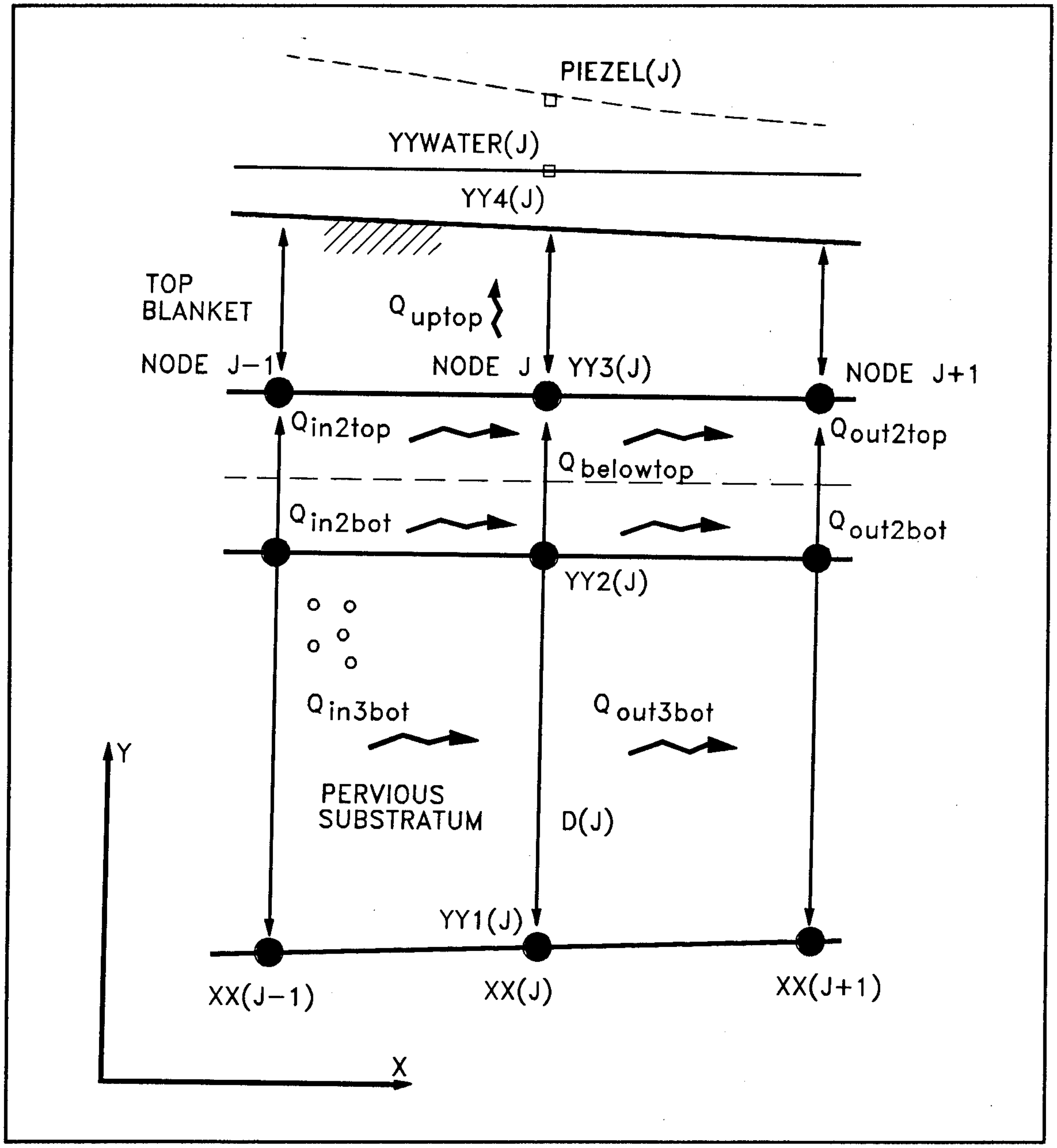


Figure 4. Three-layer underseepage model: geometry and finite difference approximation

On the riverside of the levee, the same equation is used, but Q_{uptop} and $Q_{belowtop}$ assume a negative value. Between the landside and riverside levee toes, Q_{uptop} is taken as zero.

b. *Bottom nodes.* When lumped mass balance at the bottom nodes on the landside of the levee is used, the continuity equation can be written as:

$$Q_{in2bot} + Q_{in3bot} - Q_{out2bot} - Q_{out3bot} - Q_{up2bot} = 0 \tag{11}$$

where

Q_{in2bot} = horizontal flow in the bottom half of the middle layer from the left adjacent node

Q_{in3bot} = flow within the pervious foundation from the left adjacent bottom node

$Q_{out2bot}$ = horizontal flow in the bottom half of the middle layer to the right adjacent node

$Q_{out3bot}$ = horizontal flow within the pervious foundation to the right adjacent node

Q_{up2bot} = vertical flow in the middle layer to the bottom node

On the riverside of the levee, the same equation is used but Q_{up2bot} assumes a negative value.

Solution scheme

Similar to the two-layer model, to obtain a solution for the three-layer model the system continuity equations at a number of nodes are solved by the use of an iterative scheme. Two uncoupled flow equations for the top nodes and the bottom nodes are formulated. The flow components for the top nodes are defined as:

a. Top nodes.

$$Q_{in2top} = c1top[piezeltop(j-l) - piezeltop(j)] \tag{12}$$

$$Q_{belowtop} = c2top[piezelbot(j) - piezeltop(j)] \tag{13}$$

$$Q_{uptop} = c3top[piezeltop(j) - yywater(j)] \tag{14}$$

$$Q_{out2top} = c4top[piezeltop(j) - piezeltop(J+1)] \tag{15}$$

where

$$c1top = \frac{kmh(j)}{4}\left[\frac{z2(j)+z2(j-1)}{xx(j)-xx(j-1)}\right] \tag{16}$$

$$c2top = \frac{kmv(j)}{2}\left[\frac{xx(j+1)-xx(j-1)}{z2(j)}\right] \tag{17}$$

$$c3top = \frac{kb(j)}{2}\left[\frac{xx(j+1)-xx(j-1)}{z1(j)}\right] \tag{18}$$

$$c4top = \frac{kmh(j)}{4}\left[\frac{z2(j+1)+z2(j)}{xx(j+1)-xx(j)}\right] \tag{19}$$

b. Variables in the above equations are defined as follows:

piezeltop(j) = piezometric head at node j on the top of the middle layer

piezelbot(j) = piezometric head at node j on the bottom of the middle layer

yywater (j) = elevation of ponded water at node j

kmh(j) = horizontal coefficient of permeability of middle layer at node j

xx(j) = horizontal coordinate of node j

kmv(j) = vertical coefficient of permeability of middle layer at node j

z2(j) = thickness of middle layer at node j

kb(j) = vertical coefficient of permeability of top blanket at node j

z1(j) = thickness of top blanket at node j

Substitute the flow equations into the continuity equation; then the piezometric head at any top node j, piezeltop(j), can be expressed as:

$$piezeltop(j) = \frac{c1top.piezeltop(j-1)+c2top.piezelbot(j)+c3top.yywater(j)+c4top.piezeltop(j+1)}{cltop+c2top+c3top+c4top} \quad (20)$$

To obtain a solution, use an iterative technique to solve Equation 20.

c. *Bottom nodes.* The flow components for the bottom nodes are calculated as follows:

$$Q_{in2bot} = clbot[piezelbot(j-l) - piezelbot(j)] \quad (21)$$

$$Q_{in3bot} = c2bot[piezelbot(j-l) - piezelbot(j)] \quad (22)$$

$$Q_{out2bot} = c5bot[piezelbot(j) - piezelbot(j+l)] \quad (23)$$

$$Q_{out3bot} = c4bot[piezelbot(j) - piezelbot(j+l)] \quad (24)$$

$$Q_{up2bot} = c3bot[piezelbot(j) - piezeltop(j)] \quad (25)$$

where

$$c1bot = \frac{kmh(j)}{4}\left[\frac{z2(j)+z2(j-1)}{xx(j)-xx(j-1)}\right] \quad (26)$$

$$c2bot = \frac{kf(j)}{2}\left[\frac{d(j)-d(j-1)}{xx(j)-xx(j-1)}\right] \quad (27)$$

$$c3bot = \frac{kmv(j)}{2}\left[\frac{xx(j+1)-xx(j-1)}{z2(j)}\right] \quad (28)$$

$$c4bot = \frac{kmh(j)}{4}\left[\frac{z2(j+1)+z2(j)}{xx(j+1)-xx(j)}\right] \quad (29)$$

$$c5bot = \frac{kf(j)}{2}\left[\frac{d(j+1)+d(j)}{xx(j+1)-xx(j)}\right] \quad (30)$$

d. Variables in the above equations are defined as follows:

piezelbot(j) = piezometric head at node j on the bottom of the middle layer

piezeltop(j) = piezometric head at node j on the top of the middle layer

kmh(j) = horizontal coefficient of permeability of middle layer at node j

z2(j) = thickness of middle layer at node j

xx(j) = horizontal coordinate of node j

kf(j) = horizontal coefficient of permeability of the foundation layer at node j

d(j) = thickness foundation layer at node j

kmv(j) = vertical coefficient of permeability of middle layer at node j

Substitute the flow equations into the continuity equation; then the piezometric head at any bottom node j, piezelbot(j), can be expressed as:

$$piezelbot(j) = \frac{(c1bot+c2bot).piezelbot(j-1)+c3bot.piezeltop(j)+(c4bot+c5bot).piezelbot(j+1)}{c1bot+c2bot+c3bot+c4bot+c5bot} \quad (31)$$

Use an iterative technique to obtain a solution for the piezometric heads at the bottom nodes to solve Equation 31.

Mesh Generation and Variable Node Spacing

Nodes are generated at the x coordinates specified by the user and at a number of intermediate locations. The locations of all generated nodes are

graphically displayed during the program execution. A list of node coordinates is produced as a part of the output file. The number of nodes used for analysis affects both solution accuracy and solution time. To optimize both of these factors, the node generation algorithm in LEVEEMSU produces nodes at a variable spacing.. Near the riverside and landside levee toes, where gradients are the highest and change most rapidly, nodes are generated at a maximum distance as specified by the user. Default value is 25 ft[1] and can be changed by the user during the data input phase of program execution. At progressively further distances landside and riverside from the levee toes, nodes are spaced increasingly further apart. The technique and the spacing ratios set in the program have been found to provide reasonably fast and consistent solutions with relatively few nodes.

Landside Water Elevation

The landside water elevation can be specified independently at any location. For both the two-layer and three-layer models, flow is assumed to occur vertically through the top blanket with flow gradients because of head difference between the piezometric elevation at the base of the blanket and the specified landside water elevation. In cases where landside water elevation is above the ground surface, consistent water elevation values and a sufficient number of vertical sections should be specified to accurately model the water surface profile. In cases where the landside ground is irregular, specifying the water surface coincident with the ground surface will model water rising to the surface and running off. Where landside swales are separated by relatively high ridges, the user may specify landside water surface elevations lower than the ground surface at the crowns of the ridges. At the user's discretion, water levels may vary from swale to swale.

Variable Blanket Permeability

The in situ vertical permeability of a uniformly thick top blanket during flood may be significantly different on the riverside and landside of a levee. On the riverside, downward flow may enhance siltation, plugging of cracks and defects, etc., and therefore reduce the effective permeability. On the landside, upward flow may tend to open defects in the blanket and therefore cause an increase in the permeability. These differences are modeled with LEVEEMSU by the different permeability values for the riverside and landside being specified. When the governing equations for piezometric heads are being solved, the program will check to see whether a node is riverside or landside of the levee and assign the appropriate value for permeability (k_b).

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page ix.

A further refinement allows the permeability to vary inversely as a function of blanket thickness. For levees along the lower Mississippi River, curves of permeability versus blanket thickness are often used to assign permeability values. This practice reflects the greater probability of blanket defects in thin blankets versus thick blankets. Figure 5 shows the relation between top blanket thickness and permeability used by the Lower Mississippi Valley Division (LMVD). In LEVEEMSU, this option is used to address cases of blankets with variable thicknesses. Such cases can include, for example, a ditch or borrow pit cut partly through a clay top blanket. In these cases, it is reasonable to expect a higher permeability in the ditch bottom or pit bottom than in the thicker adjacent blanket.

Wolff (1989) presented an approximate equation for the relationship presented in Figure 5 and utilized in LEVEEMSU. This equation is as follows:

$$k_b = \frac{k_{10}}{\left(\frac{z}{15} - \frac{2}{3}\right)} \tag{32}$$

where k_b is the permeability value corresponding to a blanket thickness z, and k_{10} is the permeability value in feet/minute for a 10-ft-thick blanket of a given material. It was considered more practical to provide the analyst with an infinite number of curves rather than program the curves from Figure 5 and limit the analysis to the graph data. The developed permeability equation provides permeability values versus blanket thickness that approximately parallel the LMVD curves. As shown in Figure 5, values from the permeability equation represent a family of straight lines, on semilog scale, and within the same order of magnitude as the LMVD data. However, this equation is empirically developed, and theoretical permeability values can approach zero for large magnitudes of blanket thicknesses. The use of this equation should be limited to blanket thickness equal to or less than 30 ft. When running LEVEEMSU analysis under this option, the user specifies a "curve number" or a value for k_{10}, and the program computes the corresponding blanket permeability value based on the blanket depth at each node.

Modeling a Line of Relief Wells

Rigorous analysis and design of relief wells is a three-dimensional, nonlinear problem which is beyond the scope of this report. Relief wells are approximately modeled using LEVEEMSU by specifying a constant piezometric elevation at a given x coordinate. In this case, the specified piezometric elevation represents the average head in a line of wells (H_{av}). When this option is used, the program-estimated piezometric head is forced to the assigned value at the node closest to the specified location and that node is

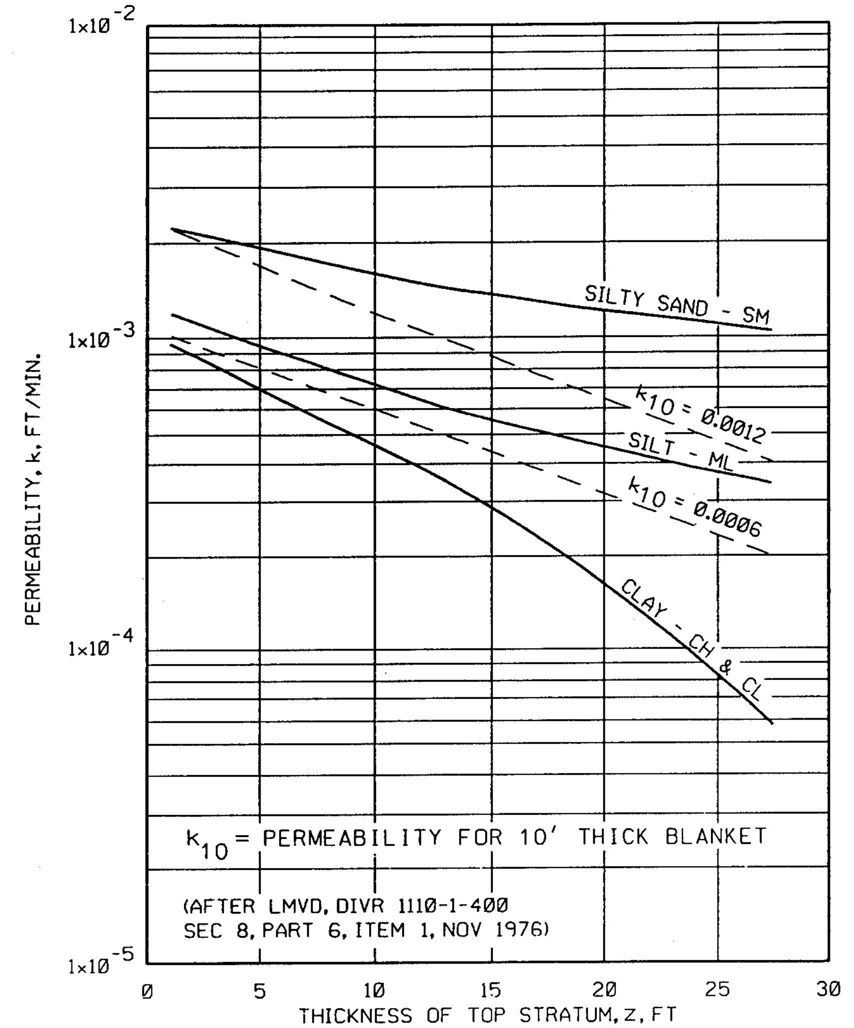


Figure 5. Blanket permeability versus stratum thickness

skipped in the iterative solution process. The program will then calculate the flow to the well line required to achieve the specified piezometric elevation as follows:

$$Q_{well} = Q_{in} - Q_{out} - Q_{up} \tag{33}$$

This scheme is illustrated in Figure 6. The analyst can then use available methods to design a well system that will accommodate a flow of Q_{well} under the specified head conditions.

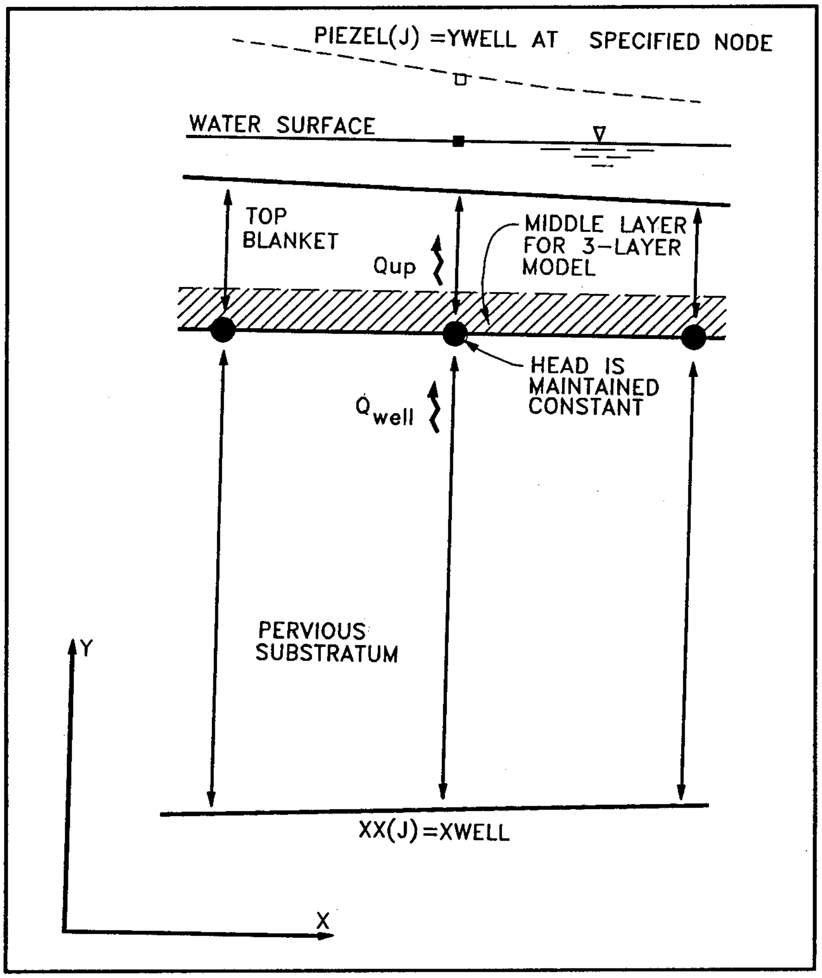


Figure 6. Analysis scheme at a relief well node

It should be mentioned that the estimated Q_{well} is based on the specified H_{av}. Nonetheless, the hydraulic head within the zone of influence of a well is variable, and the amount of Q_{well} needed to maintain H_{av} may be larger than the value computed by the program.

3 Program Description

Purpose and Identification

The main function of the computer program LEVEEMSU is the analysis of levee underseepage and control measures. The program is capable of modeling cross sections that have nonuniform geometry and variable soil properties. Solution algorithms implemented in the program utilize the finite difference method with simplified assumptions. Depending on site conditions, the subsurface strata can be idealized with a two-layer or three-layer model.

The program is furnished as a binary executable file, LEVEEMSU.EXE, designed to run on IBM (trademark or TM) and compatible personal computers under the MS DOS operating system. A math coprocessor is highly recommended. The program that was developed used Microsoft QuikBasic (TM) and was linked to required library files to produce a stand alone executable file. The BASIC computer language was selected in lieu of the more traditional FORTRAN to maximize the use of colors and graphic capabilities. Also, interactive Input/Output (I/O) interface was enhanced through the use of BASIC. The program can be run in two graphic modes, EGA color and CGA color, depending on the available graphics card, monitor, and on the desire for a graphics screen copy. In the EGA color mode, the geometry of the subsurface strata, water levels, and piezometric grade line are displayed in color. The graphic screen can be copied to a graphics printer when a screen dump program such as GRAPHICS.COM for CGA and EPSON.COM for EGA is used.

Input data for the program can be created interactively or read from a separate data file. Interactive creation of data input is described in Appendix A. Details of input data file are described later in this part of the report. During the execution of the program default values are displayed for certain variables. These default values affect the time required for solution and solution accuracy and can be changed from the keyboard. Results of the analysis are displayed on the graphic screen with a summary of the results written to an output file. This file can be printed during program execution or separately after.

Program Components

The structure of the computer program LEVEEMSU consists of a main program, and five subroutines. A flow chart showing the flow logic of the analyses procedure implemented in the program is shown in Figure 7. The following statements elaborate on the general operating system and define the function of the main program and each subroutine.

Main program

The main program is used to manage the input data and call the different subroutines for graphical preprocessing and postprocessing. The primary components of the main program are the two-layer and the three-layer models. Key analysis algorithms within the main program include development of analysis profile from input data, generating analysis nodes, assigning properties, performing the iterative solution, and saving the results. Printout of input data and output results is also achieved through the main program.

Subroutine DISPLAYTITLES

This subroutine is used for the graphical display of program title, identification, development date, and authors.

Subroutine DRAWSECTION

This subroutine is used for the graphical development of the analysis cross sections. Different boundary and geometry conditions are processed and displayed.

Subroutine GRAPHNODES

This subroutine is used for displaying the location of the generated nodes on the analysis profile.

Subroutine GRAPHPIEZ

This subroutine is used for plotting the piezometric head profile computed by the program. A plot of the piezometric head is superimposed on the analysis cross section.

Subroutine CHECKWINDOW

This subroutine is used to change the size of the area displayed on the screen by zooming on the specific area of interest. This subroutine provides the user with the option of displaying and printing the area of interest with a high resolution.

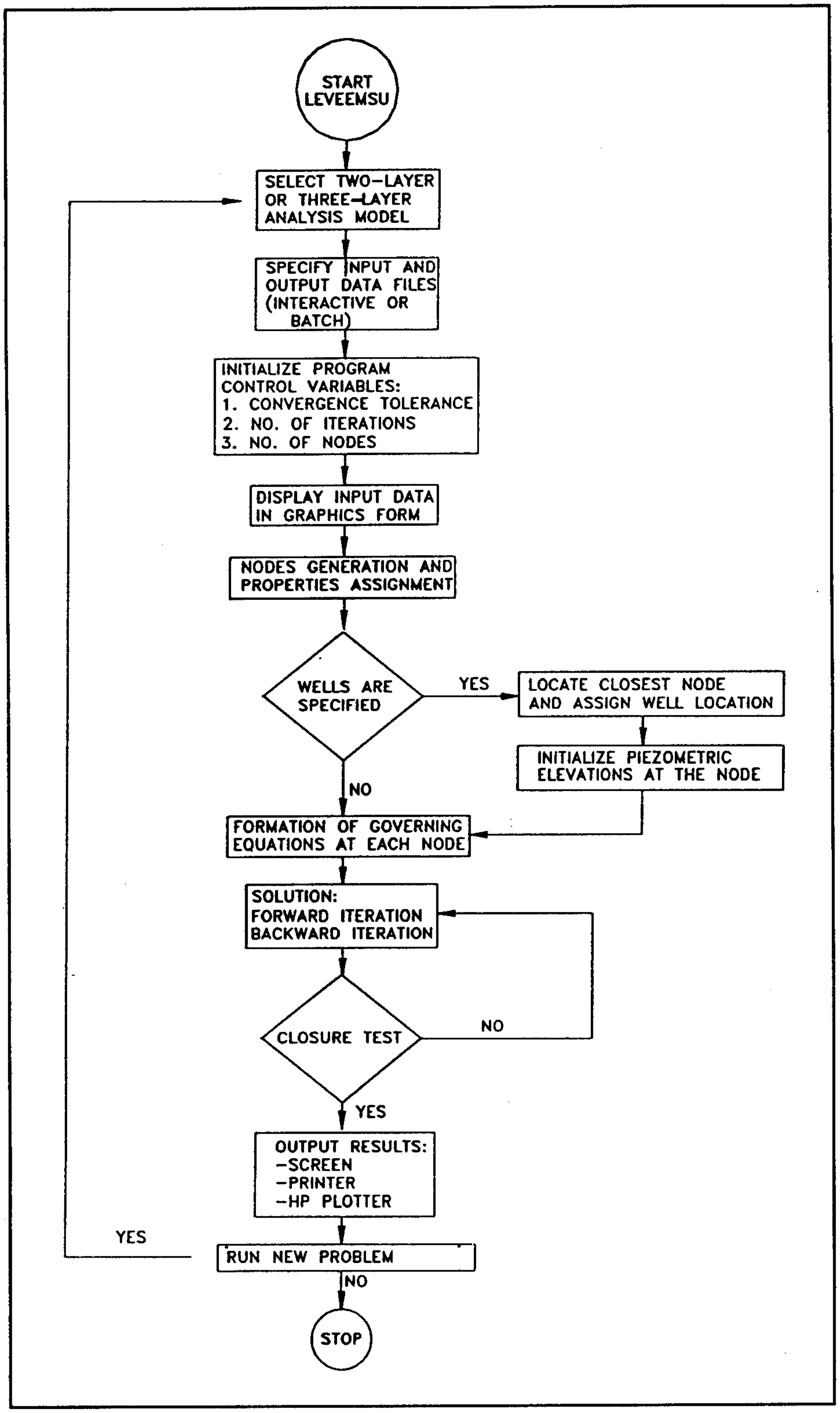


Figure 7. Flow chart of analysis logic

Sign Convention and Coordinate System

Data input is based on a coordinate system in which the bottom left handside point of the flow domain is the origin, the positive x-direction is to the left, and the positive y-direction is upward, as shown in Figure 8. User-defined vertical profiles at different x locations have to be input in the upward and positive y-direction. The sign conventions for gradients are shown in Figure 8, and hydraulic heads are always assumed to be greater than zero. The sign convention for gradients is indicative of direction with a positive gradient being in the upward direction and a negative gradient being in the downward direction.

Units

English or metric units can be used with LEVEEMSU for input data. However, when English units are used, only feet and minutes are allowed; when Metric units are used, only meters and minutes are allowed. Accordingly, the output results will be in the same units. It should be noted that the accuracy of solution may be affected if the user uses metric units but maintains the default values implemented in the program for node spacing and convergence tolerance. These values are in feet, and if metric units are used for distances, the default maximum node spacing will be 25 m with a convergence tolerance of 0.005 m. The user should change these default values according to the units to be used.

Input Data

Input data can be created in an interactive mode or in a batch mode. Creating data files in an interactive mode is described in Appendix A with definition of variables and control flags. All input data are free formatted, and a space is the only requirement to separate one input variable from another. The program also accepts the data input in a batch form. Description of input data files and an easy to follow guide for creation of these files is given below:

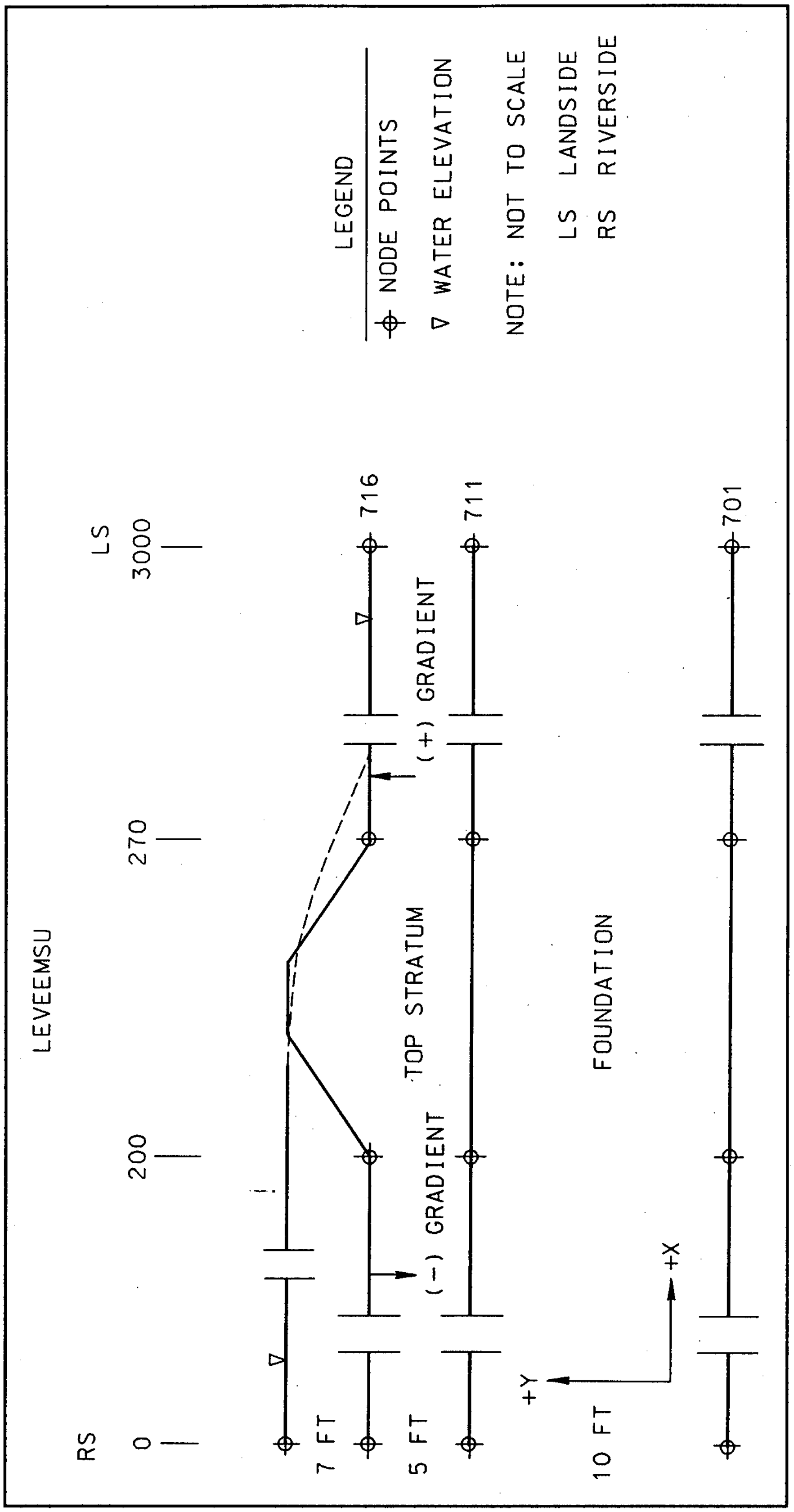


Figure 8. Sign convention and coordinate system

Job Project
Variable : TITLE1$
Number of Lines: 1
Explanation :
Description of the job to be run. Any characters are allowed.

Project Number, Date, and Operator
Variable : TITLE2$
Number of Lines: 1
Explanation :
Number assigned to the job, date and name of operator performing the analysis or running the program. Any characters are allowed.

Foundation Permeability
Variable : KF
Number of Lines: 1
Explanation :
Permeability value of the foundation layer.

Permeability Values for Middle Layer (Riverside): Three-Layer Model Only
****(Omit This Line for Two-Layer Model)****
Variables : KMVR, KMHR
Number of Lines: 1
Explanation :
KMVR = vertical permeability of the middle layer on the riverside in m/min or ft/min.
KMHR = horizontal permeability of the middle layer on the riverside in m/min or ft/min.

Cross Section and Blanket Properties- Riverside
Variables : NRIVSECS, PERMFLAGR$, PERMRIV, YRIV
Number of Lines: 1
Explanation :
NRIVSECS = number of vertical sections used to describe the problem geometry on the riverside of the levee. NRIVSECS must be two (2) or more. The first section is an open entrance; the last section is the riverside toe of the levee.

PERMFLAGR$ = a flag that indicates how the riverside permeability is to be specified. Use the value "CONST" or "const" to specify a constant riverside blanket permeability. Use the value "CURVEM" or "curvem" to calculate the riverside blanket permeability as a function of the blanket thickness "z" when permeability values are in m/min. Use the value "CURVEE" or "curvee" when permeability values are in ft/min.

PERMRIV = Vertical permeability of the riverside top blanket if PERMFLAGR$ is "CONST". If PERMFLAG$ is "CURVE", PERMRIV is the vertical permeability for a blanket thickness of 10 ft if using English units or 3 m if using Metric units. The program will use the method described in Chapter 2 to calculate the permeability for other thicknesses.

YRIV = riverside water elevation.

Cross Section (Riverside): Two-Layer Model
****(Omit These Lines for Three-Layer Model)****
Variables : X(NRIVSECS), Y1(NRIVSECS), Y2(NRIVSECS), Y3(NRIVSECS)
Number of Lines: NRIVSECS (minimum of two cards)
Explanation :
X(NRIVSECS) = the x coordinate defined with reference to the (0,0) point
Y1(NRIVSECS) = the base of the pervious substratum
Y2(NRIVSECS) = the top of the pervious substratum/base of the top blanket
Y3(NRIVSECS) = top of the ground surface

Cross Section (Riverside): Three-Layer Model
****(Omit These Lines for Two-Layer Model)****
Variables : X(NRIVSECS), Y1(NRIVSECS), Y2(NRIVSECS), Y3(NRIVSECS), Y4(NRIVSECS)
Number of Lines: NRIVSECS (minimum of two cards)
Explanation :
X(NRIVSECS) = the x coordinate defined with reference to the (0,0) point
Y1(NRIVSECS) = the base of the pervious substratum
Y2(NRIVSECS) = the top of the pervious substratum/base of the bottom layer
Y3(NRIVSECS) = top of the middle layer/base of the top blanket
Y4(NRIVSECS) = top of the ground surface

Permeability Values for Middle Layer (Landside): Three-Layer Model Only
****(Omit This Line for Two-Layer Model)****
Variables : KMVL, KMHL
Number of Lines: 1
Explanation :
KMVL = vertical permeability of the middle layer on the landside in m/min or ft/min.
KMHL = horizontal permeability of the middle layer on the landside in m/min or ft/min.

Cross Section and Blanket Properties - Landside

Variables : NLANDSECS, PERMFLAGL$, PERLAND

Number of Lines: 1

Explanation :

NLANDSECS = the number of vertical sections used to describe the problem geometry on the landside of the levee. This value must be two or more. The first section is the landside toe of the levee; the last section is an open exit.

PERMFLAGL$ = a flag that indicates how the riverside permeability is to be specified. Use the value "CONST" or "const" to specify a constant riverside blanket permeability. Use the value "CURVEM" or "curvem" to calculate the riverside blanket permeability as a function of the blanket thickness "z" when permeability values are in m/min. Use the value "CURVEE" or "curvee" when permeability values are in ft/min.

PERMLAND = Vertical permeability of the riverside top blanket if PERMFLAGL$ is "CONST". If PERMFLAGL$ is "CURVE", PERMLAND is the vertical permeability for a blanket thickness of 10 ft if using English units or 3 m if using Metric units. The program will use the method described in Chapter 2 to calculate the permeability for other thicknesses.

Cross Section (Landside): Two-Layer Model

****(Omit These Lines for Three-Layer Model)****

Variables :	X(NLANDSECS), Y1(NLANDSECS), Y2(NLANDSECS), Y3(NLANDSECS), YWATER(NLANDSECS)
Number of Lines:	NLANDSECS (minimum of two cards)
Explanation :	
X(NLANDSECS) =	the x coordinate defined with reference to the (0,0) point
Y1(NLANDSECS) =	the base of the pervious substratum
Y2(NLANDSECS) =	the top of the pervious substratum/base of the top blanket
Y3(NLANDSECS) =	top of the ground surface

YWATER(NLANDSECS) = the elevation of the free water surface. Based on the analysis assumption of fully saturated flow media, this value has to be specified as equal to or above the ground surface elevation.

Cross Section (Landside): Three-Layer Model
****(Omit These Lines for Two-Layer Model)****

Variables : X(NLANDSECS), Y1(NLANDSECS), Y2(NLANDSECS), Y3(NLANDSECS), Y4(NLANDSECS), YWATER(NLANDSECS)

Number of Lines: NLANDSECS (minimum of two cards)

Explanation :

X(NLANDSECS) = the x coordinate defined with reference to the (0,0) point

Y1(NLANDSECS) = the base of the pervious substratum

Y2(NLANDSECS) = the top of the pervious substratum/base of the bottom layer

Y3(NLANDSECS) = top of the middle layer/base of the top blanket

Y4(NLANDSECS) = top of the ground surface

YWATER(NLANDSECS) = the elevation of the free water surface. Based on the analysis assumption of fully saturated flow media, this value has to be specified as equal to or above the ground surface elevation.

Option for Relief Wells Analysis

Variables : WELLFLAG$

Number of Lines: 1

Explanation :

A flag which tells the program to read one additional line giving a specified piezometric elevation at one location, which can be used to simulate a line of relief wells. If a relief well (or specified piezometric head) is to be specified, enter the word "WELL" or "well" on this line. If this option is not desired, enter any other word(s), such as NO WELLS, STOP or END.

Relief Wells Data
****(Omit This Line for No Relief Wells)****

Variables : XWELL, YWELL

Number of Lines: 1

Explanation :

The following variables are only used if WELLFLAG$ is "WELL" or "well": XWELL is the "x" coordinate where the piezometric elevation is to be specified. If a node is not generated at this location, the program will move it to the nearest node. It is recommended that this value be the same as the "x" coordinate of one of the specified landside sections. YWELL is the "y" coordinate of the specified piezometric elevation at XWELL. The piezometric elevation will be forced to the specified value at the specified location. It is equivalent to the average piezometric elevation in a line of wells.

Output Information

Output results mainly consist of graphical data and tables showing the variation of the piezometric head and gradient as a function of location. For each successful execution, the program output is directed to three output devices. These output devices include the screen, printer, and default computer drive (default drive is the drive that contains the diskette from which the program is loaded and run). The output results are graphically displayed on the screen, whereby the estimated piezometric head profile is superimposed on the problem geometry. The user can obtain a copy of this plot through the use of "print screen" option. Also, the program will prompt the user the option of sending the output tables to the printer. The output tables contain key input information and the analysis results. These tables are also stored on the computer drive. The process of running LEVEEMSU is presented in Appendix B with example runs, and output data for the two-layer and three-layer models are presented in Appendix C.

4 Program Testing and Parametric Studies

Closure Tolerances, Node Spacing, and Number of Iterations

The analysis algorithm implemented in the program is based on numerical modeling of the flow domain and geometric conditions. Successive iterations of the governing model at discrete nodes produce converging solutions. The iteration procedure is stopped when the maximum residual error (change in calculated piezometric head at any node between successive iterations) is less than a specified closure tolerance.

In general, the closure tolerance must be significantly less than the desired accuracy of the solution since small changes from one iteration to the next may accumulate toward the "exact" solution. Smaller node spacings and closure tolerances yield more accurate solutions but require a longer run time.

Standard input data file labeled DATACHK for the two-layer model (listed in Appendix A) was used to initially check program solution and evaluate relationships among tolerance, node spacing, and number of iterations. According to this input file, levee and subsurface conditions with the following parameters were modeled:

<u>Two-Layer Model:</u>
Pervious Foundation: $D = 80$ ft
Top Blanket: $z = 10$ ft
Foundation Lengths: $L_1 = 1{,}500$ ft, $L_2 = 300$ ft, $L_3 = 3{,}200$ ft
Permeability: $k_f = 0.2$ ft/min, $k_b = 0.0002$ ft/min
The final screen output for a run with DATACHK and default options is shown in Figure 9. As shown, the program calculates a maximum residual head of 8.87 ft and a maximum gradient of 0.89, both occurring at the landside toe ($x = 1{,}800$ ft).

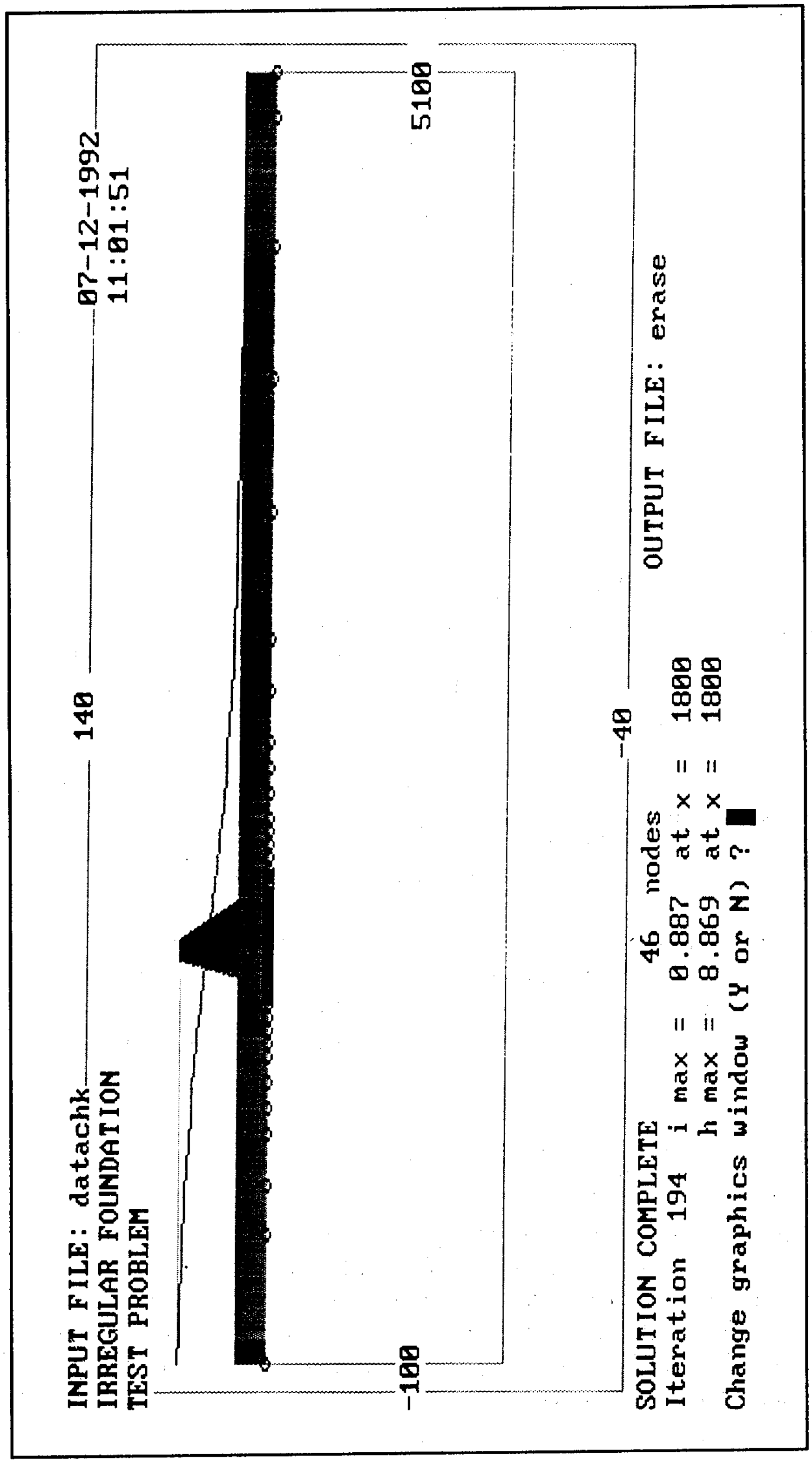


Figure 9. Copy of screen output, file DATACHK

Detailed sensitivity study using the geometry defined in DATACHK was conducted by Wolff (1989) to investigate the influence of node spacing and convergence tolerance on calculated maximum gradient and number of iterations required for solution. Results from this study indicated that, for the specified problem geometry, a node spacing of 25 ft or less and a convergence tolerance of 0.0005 ft are sufficient to calculate a gradient within a few hundredths of the theoretical value of 0.88 as obtained from the application of analytical equations to the same problem. A node spacing of 50 ft was too coarse to accurately calculate the gradient because of the averaging of upward flow conditions near the toe over a large horizontal distance. Use of a 50-ft node spacing caused the theoretical maximum gradient to be overpredicted by approximately 7 percent.

Based on the above analyses, program default parameters were set at a node spacing of 25 ft and a convergence tolerance of 0.0005 ft. These values can be changed at the user's discretion during program execution. Finer node spacings or finer tolerances will increase the number of iterations and therefore the solution time. In case of the three-layer model, relationships between tolerance, node spacing, and number of iterations are assumed to be similar to results obtained for the two-layer model. The user should note that default values for node spacing and closure tolerance are in feet and should be changed if metric units are used.

Model Verification

Results from a two-layer calculation are checked by performing a manual analysis for the problem represented by the input data file DATACHK (Appendix C). The program output is shown in Appendix C with the manual analysis results shown in Appendix E. The program assumes an open seepage exit at the last specified section 3,000 ft landward of the levee toe. In the manual analysis, L_3 distances of both 3,000 ft and infinity were checked. The computer and manual solutions are compared in Figure 10 in which the residual head is plotted as a function of the distance from the landside levee toe. It was concluded that, compared to the manual solution, an L_3 distance of 3,000 ft was needed to accurately model an infinitely long exit condition for this case.

No manual analytical procedure is available to check the accuracy of the three-layer model. However, several runs are made to ensure that the solution algorithms implemented in the three-layer model are robust. Standard input file labeled DATACHK3 for the three-layer model (listed in Appendix D) was used for this purpose. According to this input file, levee and subsurface conditions with the following parameters were modeled:

Three-Layer Model:
Pervious Foundation: D = 70 ft
Middle Layer: z2 = 10 ft
Top Blanket: z1 = 10 ft

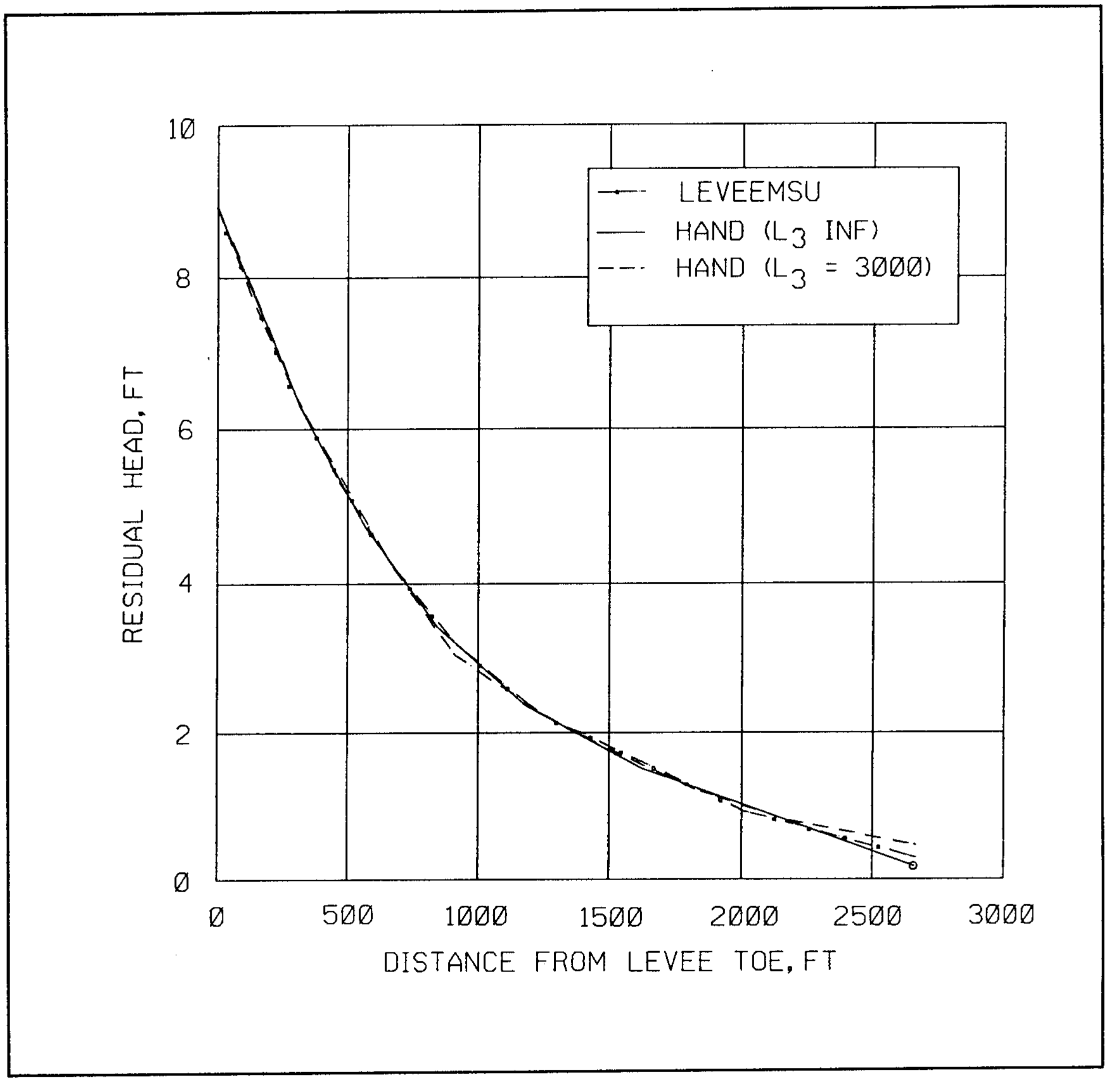


Figure 10. Residual head versus distance from levee toe, file DATACHK (from Wolff 1989)

Foundation Lengths: L_1 = 1,500 ft , L_2 = 300 ft , L_3 = 3,200 ft
Permeability: k_f = 0.2 ft/min, k_b = 0.0002 ft/min
The permeabilities assumed for the middle layer were as follows:

	kmv (ft/min)		
kmh (ft/min)	kmh/kmv 1	5	10
0.0002	0.0002	0.00004	0.00002
0.002	0.002	0.0004	0.0002
0.2	0.2	0.04	0.02

A case of particular interest is when kmh = kmv. Use this case so that the middle layer can be modeled as either a part of the top blanket or a part of the pervious foundation layer. Setting the analysis parameters in such fashion will cause the three-layer model to simulate a two-layer model. The analysis cases conducted according to this configuration are as follows:

Case	Two-Layer Model	Three-Layer Model
1	D = 70 ft z = 20 ft k_f = 0.2 ft/min k_b = 0.0002 ft/min	D = 70 ft z1 = 10 ft z2 = 10 ft k_f = 0.2 ft/min k_b = 0.0002 ft/min kmh = 0.0002 ft/min kmv = 0.0002 ft/min
2	D = 80 ft z = 10 ft k_f = 0.2 ft/min k_b = 0.0002 ft/min	D = 70 ft z1 = 10 ft z2 = 10 ft k_f = 0.2 ft/min k_b = 0.0002 ft/min kmh = 0.2 ft/min kmv = 0.2 ft/min

Standard output from the three-layer model is shown in Figure 11 with the middle layer assumed to be a part of the top blanket and, a part of the pervious foundation in Figure 12. Comparison of piezometric head results from the two-layer model with results from the three-layer model for cases 1 and 2 are presented in Figure 13. Heads estimated with the three-layer model differ from those estimated with the two-layer model by 0.02 ft for case 1 and 0.14 ft for case 2. However, such a difference was expected since, contrary to the two-layer model, both horizontal and vertical flows are allowed through the middle layer for the three-layer model. For larger permeabilities of the middle layer, this difference becomes more pronounced as observed from the results for case 2 versus case 1. Nonetheless, these results confirm the validity of the three-layer model.

Exit gradient through the top layer shown in Figure 14 resulted from the use of different permeability ratios for the middle layer. In the case of kmh=0.2, the system reduces to two-layer model with the middle layer primarily acting as a part of the pervious foundation layer. In case of kmh = 0.0002, the middle layer is acting as a part of the top clay blanket. As the permeability value of the middle layer is increased, the head loss within the domain is decreased; therefore, higher exit hydraulic gradients on the top blanket are estimated.

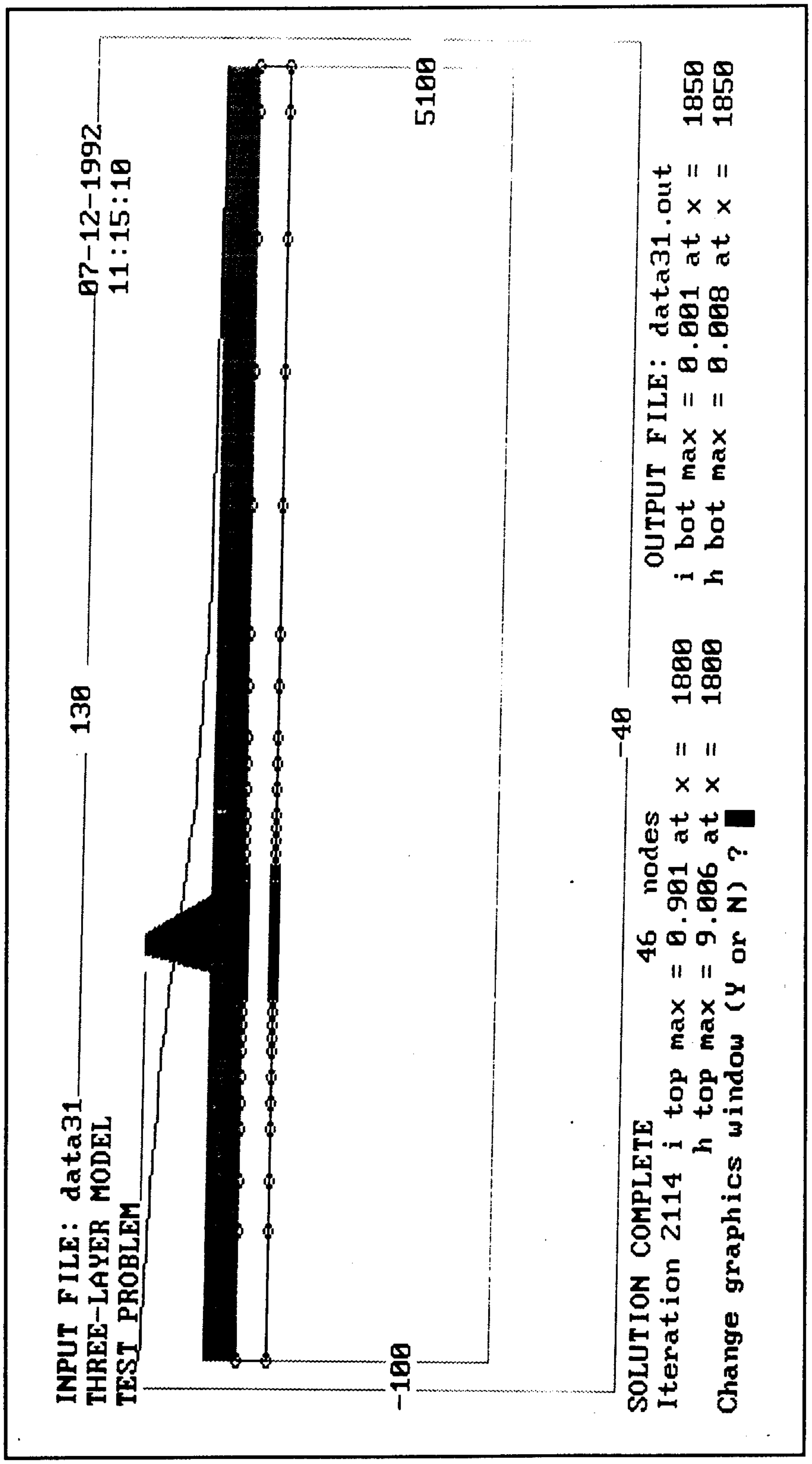


Figure 11. Copy of screen output: three-layer model with middle layer as part of the foundation

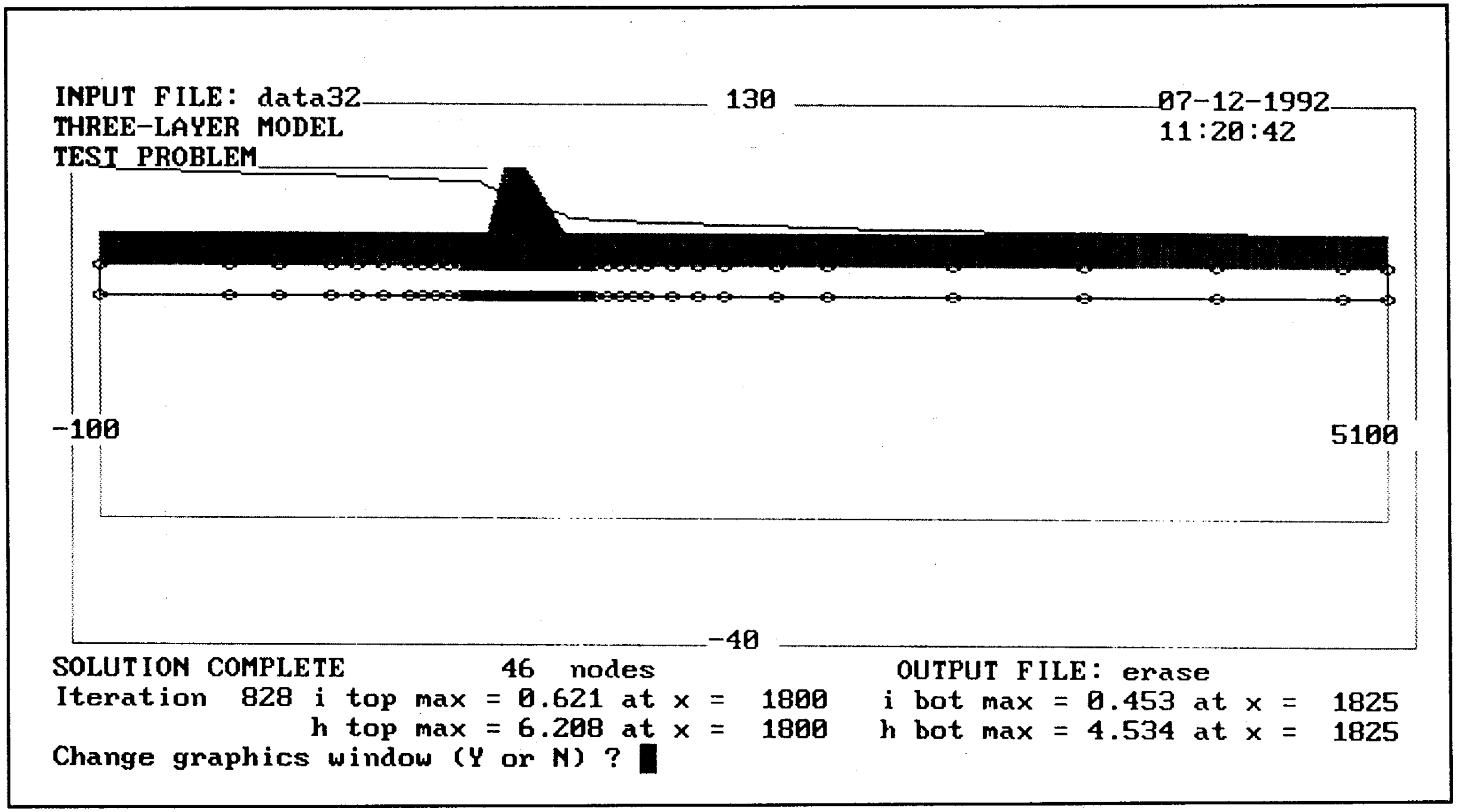


Figure 12. Copy of screen output: three-layer model with middle layer as part of the top blanket

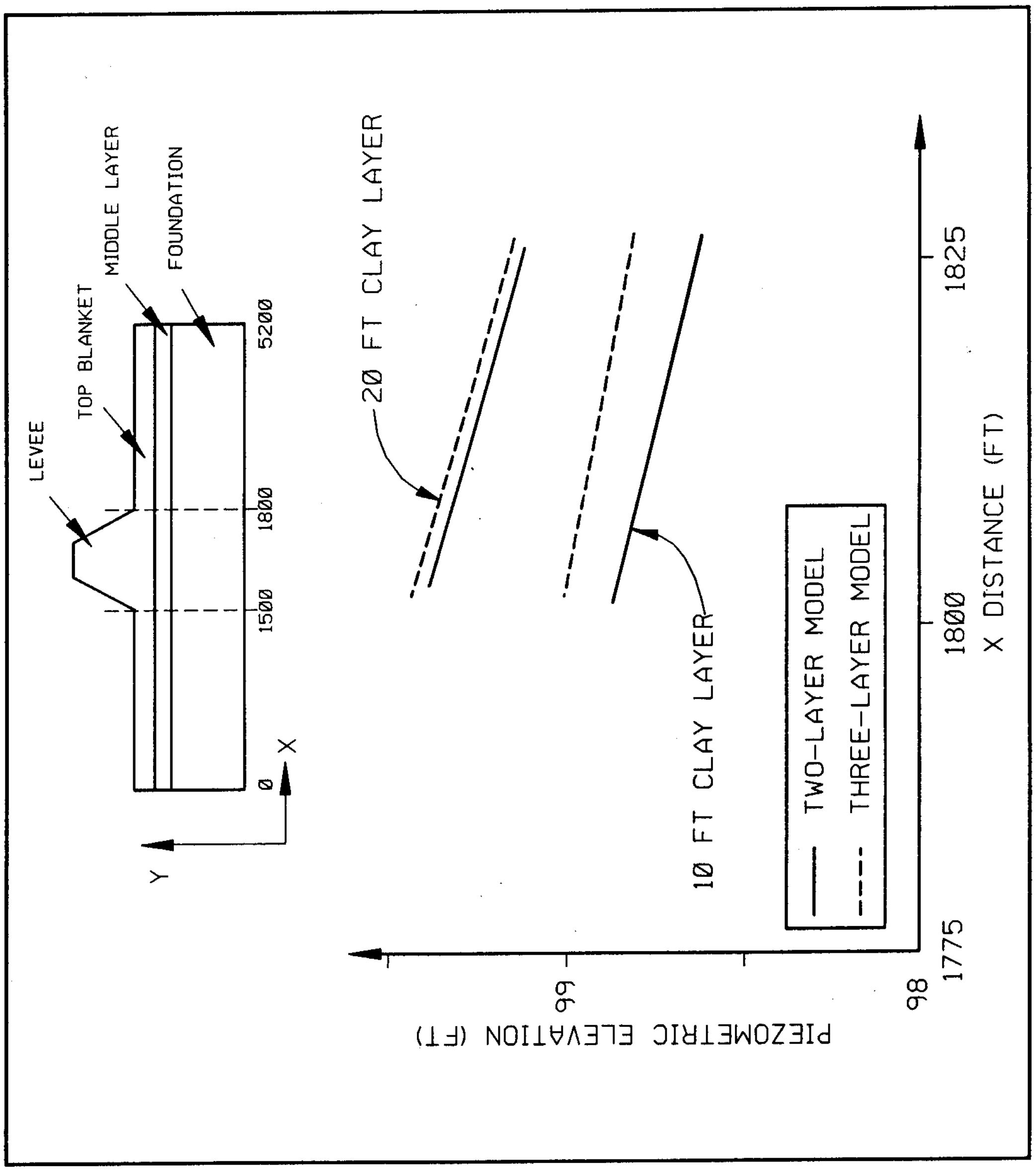


Figure 13. Comparison of three-layer model with two-layer model

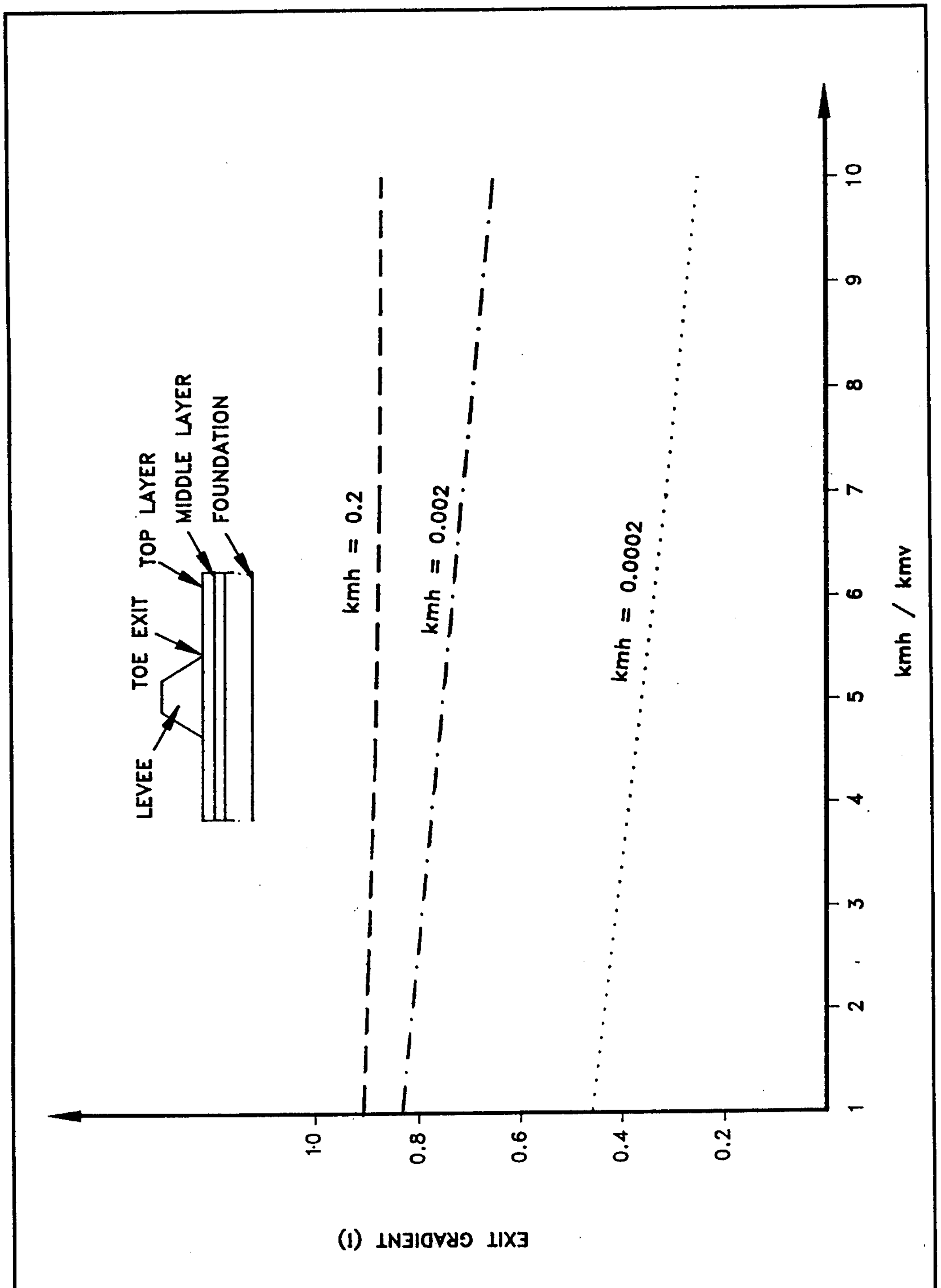


Figure 14. Exit gradient versus permeability ratio of the middle layer

Modeling Finite and Infinite Geometry

LEVEEMSU always models open entrance and exit conditions at the first and last specified vertical sections. To approximate infinitely long entrance (L_1) or exit (L_3) distances, specify the beginning or ending sections at very large distances from the levee. To investigate how great such distances should be, a parameter study was performed by Wolff (1989) in which different exit lengths, L_3, were modeled. The two-layer model was used in this study with the input data file DATACHK. Results are shown in Figure 15. It was concluded that for the geometry and subsurface conditions modeled in this study, results approach the analytical solution when L_3 exceeds 2,000 to 3,000 ft, or in this case, approximately 20 to 30 times the thickness of the pervious substratum. It would appear that such a ratio should properly model infinitely long foundations; however, users are cautioned to make their own parametric studies for cases where accuracy is critical. Users are further cautioned that the distance to effective seepage exit, x_3, is a mathematical concept used in conventional analysis, and not any measure of levee geometry. Specifying the last vertical section at some calculated x_3 distance will generally result in calculated gradients that are too low, as some seepage always exits the blanket beyond the x_3 distance.

Effects of Blanket Permeability

To assess the consistency of program behavior with respect to input permeability, a series of parametric studies were performed by Wolff (1989). The data file DATACHK was used with assumed permeability ratio k_f/k_b = 1,000 on both the riverside and landside of the levee. The input data were altered by keeping the landside permeability and permeability ratio constant (k_f/k_{b1} = 1,000) and varying the riverside permeability ratio k_f/k_{br} from 1 to 1,000. Then the riverside permeability was held constant, and the landside permeability ratio changed in a similar fashion. Calculated maximum gradients are plotted versus permeability ratio in Figure 16. It is seen that the program exhibited consistent and expected behavior, with the gradient increasing with increasing riverside permeability or decreasing landside permeability, and vice versa.

Effects of Sloping Ground

Modeling sloping ground surface in LEVEEMSU should be limited to slopes on the order of or less than 100 horizontal (H) to 1 vertical (V). Sloping profiles can include sloping of the ground surface due to man-made alterations or the consistent sloping of the subsurface strata due to geologic factors. As the flow domain is sloped, the assumptions of only horizontal flow in the foundation layer and only vertical flow in the top blanket are violated. For a sloping profile, the water in the foundation layer will flow with the same orientation as the slope. The assumption of only horizontal

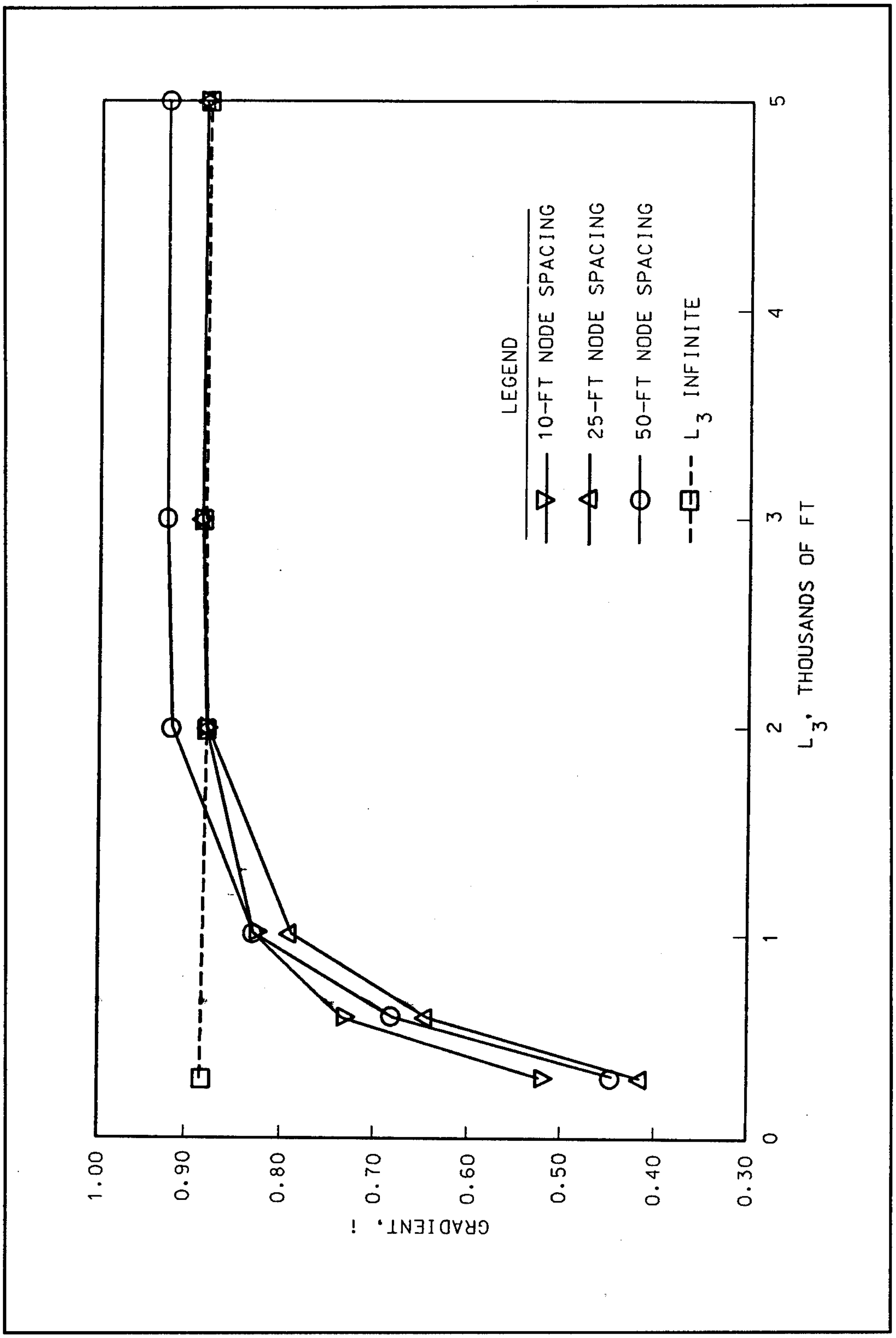


Figure 15. Gradient versus open exit length (L_3), two-layer model (after Wolff 1989)

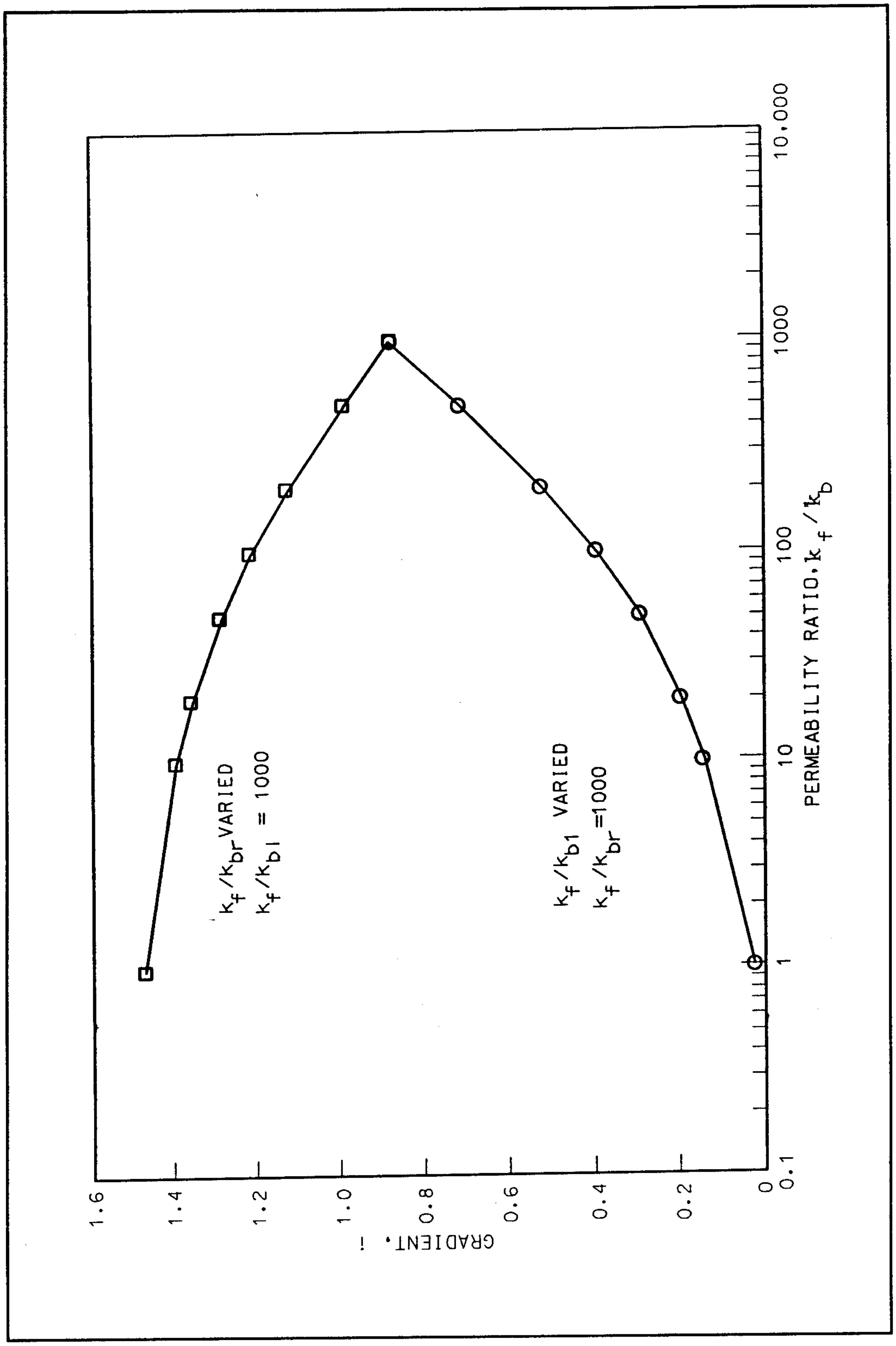


Figure 16. Effect of assumed permeability ratio on maximum gradient: two-layer model (after Wolff 1989)

flow in this layer ignores a vertical flow component that may significantly impact the results. A parameter study was conducted by Wolff (1989) to assess the feasibility of using LEVEEMSU in case of sloping profiles. Results indicated that an infinite ground slope as little as ½ to 1 percent can have significant effects on the predicted gradient. Conventional analysis procedures provide no means to assess such effects, and the user should not overextend the use of the program where geometry conditions differ from assumptions made during model development.

Effects of Ditches

A common problem in underseepage analysis is assessing the effects of landside ditches and determining minimum distances that ditches should be set back from a levee to provide acceptable gradients. These effects can be assessed using LEVEEMSU. Wolff (1989) presented such analyses using a file named DATADCH (Appendix D). This file was created and systematically modified to vary the distance between the landside levee toe and ditch crown and to vary ditch depth. In all cases, the ditch had a 10-ft-bottom width and 1V on 3H side slopes. The foundation had a substratum thickness of 65 ft and a top stratum thickness of 15 ft. Both constant blanket permeability (PERMFLAG = "CONST") and variable (PERMFLAG = "CURVE") blanket permeability conditions were modeled. A typical screen output for this problem is shown in Figure 17. In the case of a 5-ft-deep ditch more than about 300 to 350 ft from the levee toe, the gradient at the levee toe (0.61) exceeds the gradient at the ditch for the conditions modeled. A 10-ft-deep ditch results in excessively high gradients even at distances as far as 600 ft from the levee. Results of the study are summarized in Figure 18. The sections modeled with variable ("CURVE") blanket permeabilities have lower permeability values except at the ditch. With the curve option, the specified permeability is for a 10-ft-thick blanket in the ditch; the program adjusts the k for a thickness greater than 10 ft to the permeability for a 10-ft blanket at the ditch and a 15-ft blanket away from the ditch.

Effects of Riverside Borrow Pits

Another common analysis problem is assessing the effects of borrow pit distance and depth on underseepage conditions for new levees or the effects of borrow pit enlargement for raising existing levees. This problem is essentially the same as the ditch problem but usually alters geometry on the riverside of the levee. The results of an example are shown in Figure 19. The input data of file DATACHK were modified to model the geometry of a riverside borrow pit 300 ft wide and 5 ft deep with 1V on 3H side slopes at different distances from the levee toe. These results are shown in Figure 20. It is noted that moving a borrow pit closer to the levee increases the gradient as expected, but the effect is much less severe than cutting ditches on the landside.

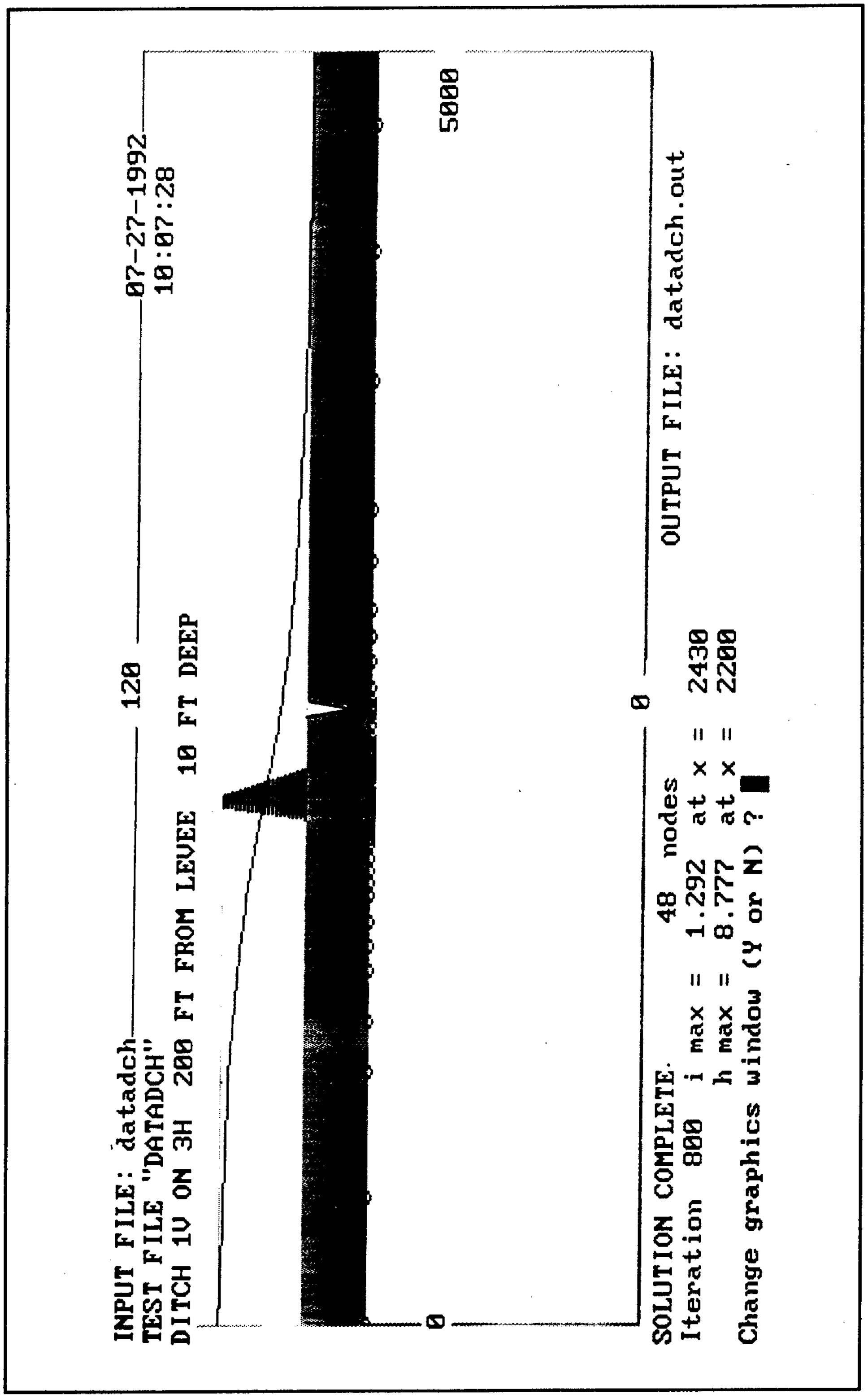


Figure 17. Copy of screen output, ditch study

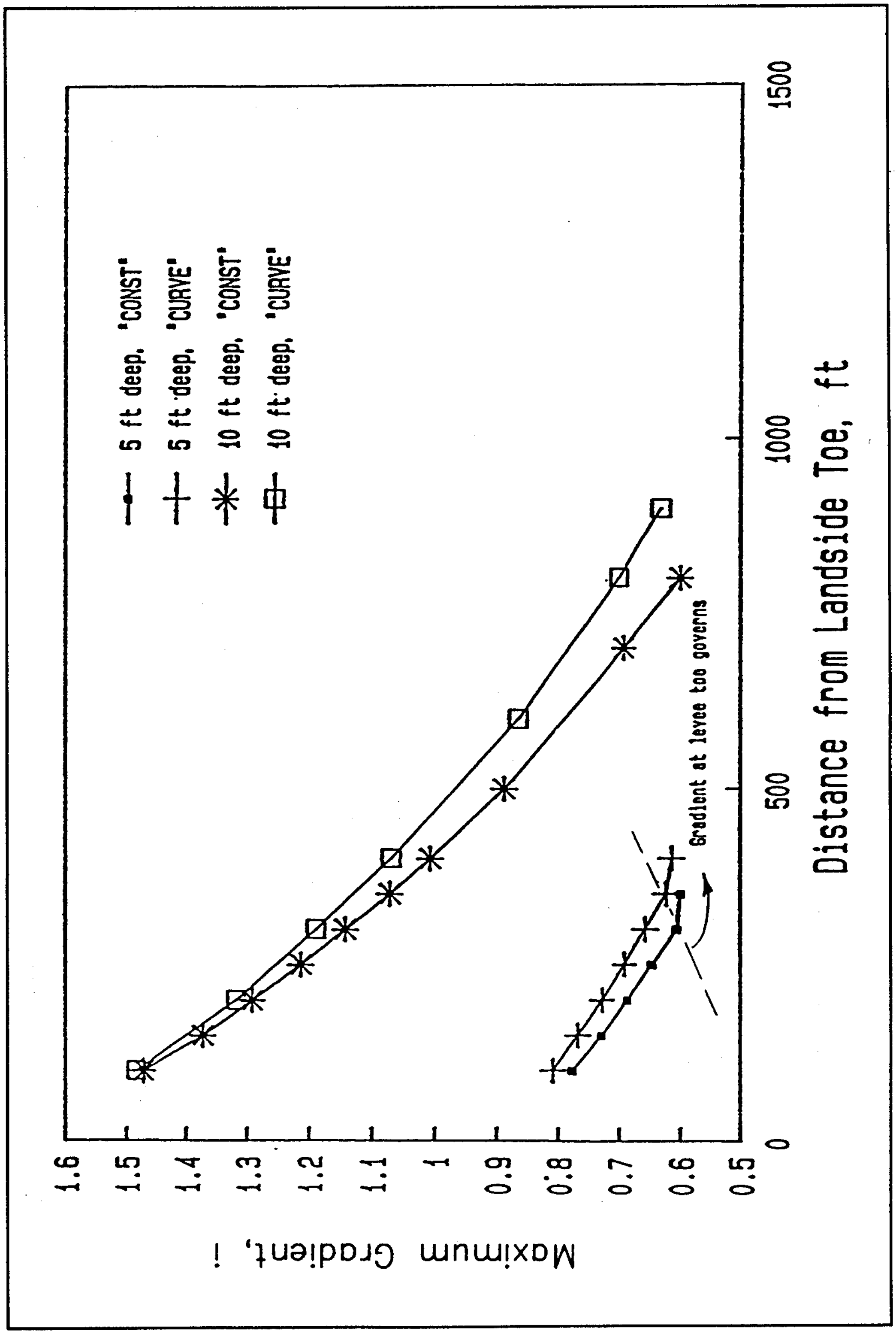


Figure 18. Maximum gradient versus ditch size and location (after Wolff 1989)

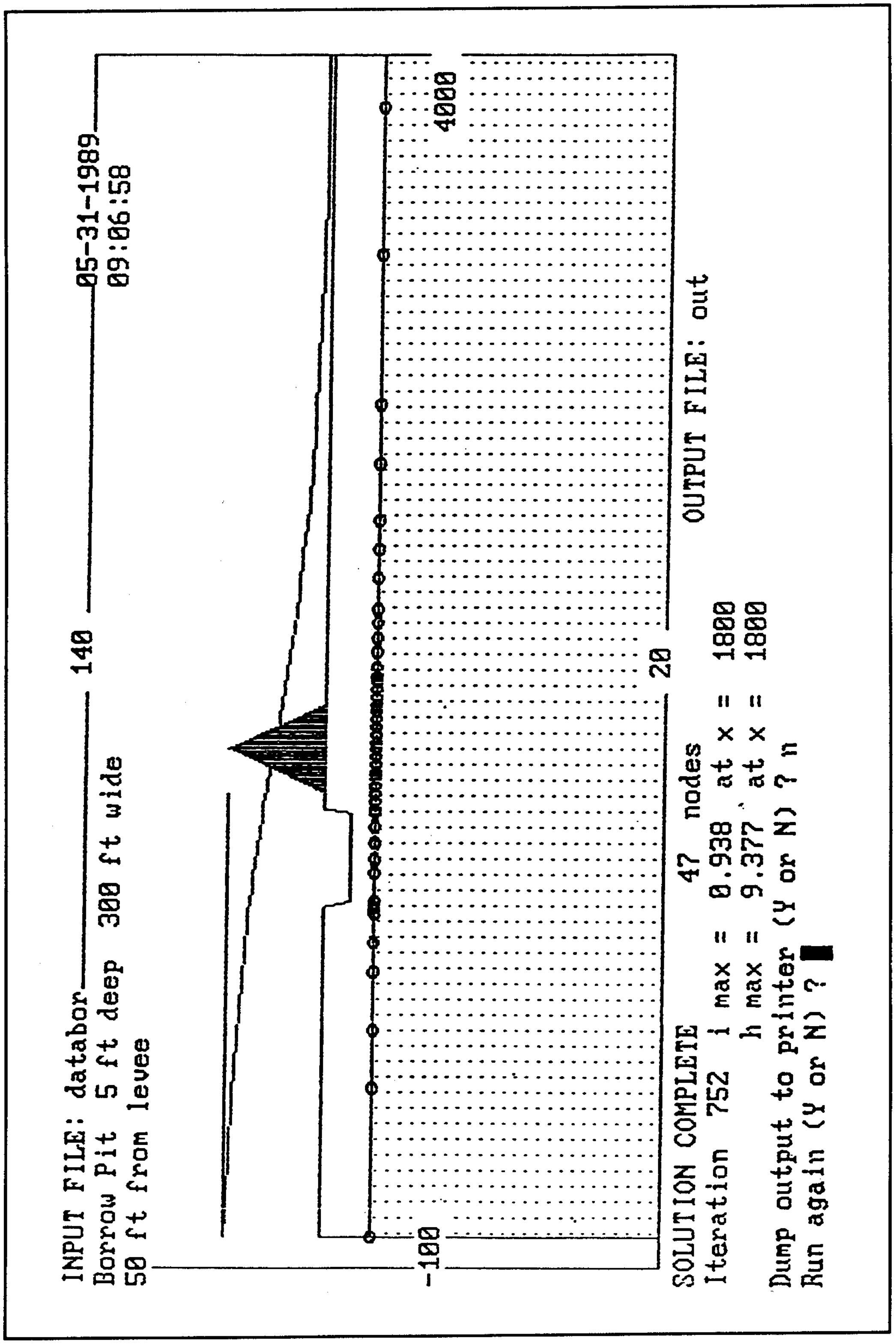


Figure 19. Copy of screen output, borrow pit study (after Wolff 1989)

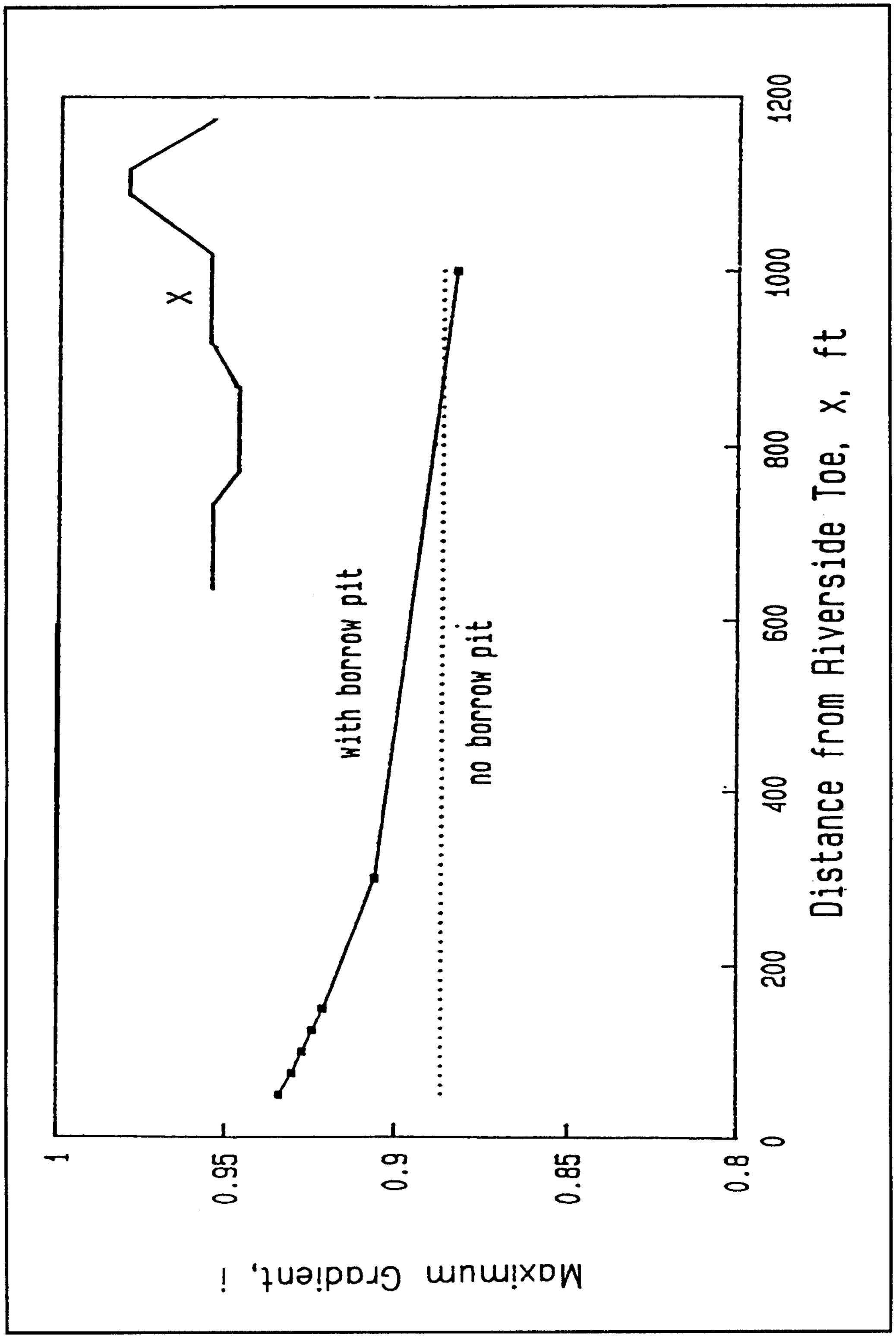


Figure 20. Results of borrow pit study (after Wolff 1989)

Effects of Relief Wells

LEVEEMSU provides the capability to approximately model the effects of a line of relief wells by specifying the piezometric head at one landside location. The program calculates the well flow per unit length of levee required to reduce the average piezometric elevation in the well line to the specified value. The user must then design a well system consistent with these results. Relationships obtained between piezometric elevations and well flow do not include hydraulic losses or partial penetration effects at individual wells. These relationships should, however, be useful for preliminary assessments of the need for wells and likely numbers and spacing.

To assess the program's capability in handling relief well behavior, two parametric studies were performed with the input file DATAWELL, which is essentially the file DATACHK modified to specify a well line at the levee toe. In the first study, the specified piezometric elevation in the well line was varied. Results are shown in Figure 21. In this figure, both maximum gradient and well flow are plotted versus the specified average head at the well line. Results of such analysis can be used for preliminary design. For example, if it is desired to reduce the gradient to 0.7, the figure shows that a well system must be designed that will reduce the average piezometric elevation at the well line to el 97. Therefore, the system must be capable of passing approximately 0.5 gallon per minute (gpm) per foot of levee. The specified piezometric elevation resulting in zero well flow is 98.87 ft, which matches the residual head of 8.87 ft obtained for the analysis of DATACHK without wells. In the second parametric study, the specified piezometric elevation was maintained constant, and the foundation permeability was varied. Results are shown in Figure 22. As expected, well flow varies in proportion to the foundation permeability with only a minor change in gradient.

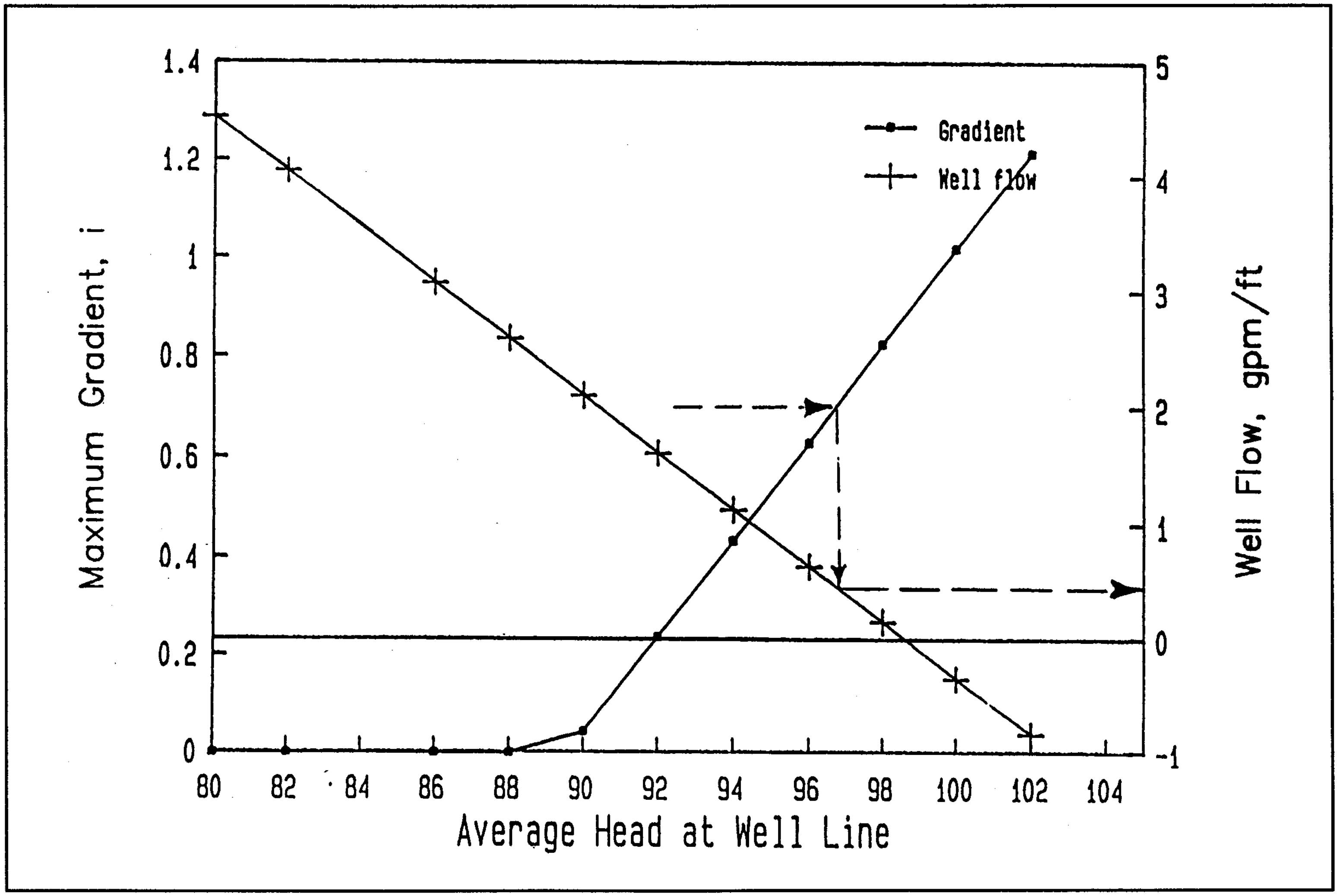


Figure 21. Maximum gradient and well flow versus average head in well line, file DATAWELL (after Wolff 1989)

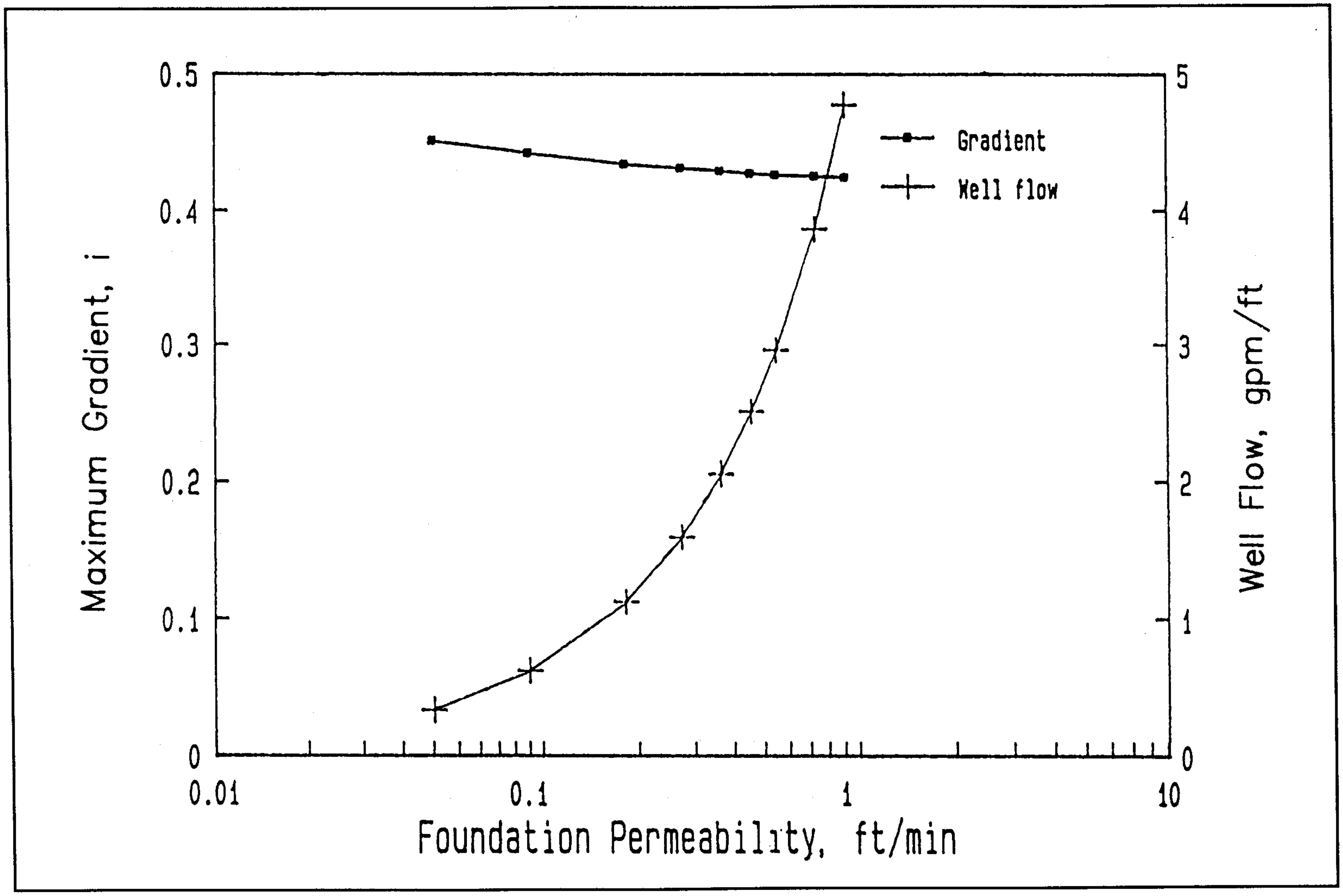


Figure 22. Maximum gradient and well flow versus foundation permeability, file DATAWELL (after Wolff 1989)

5 Program Limitations

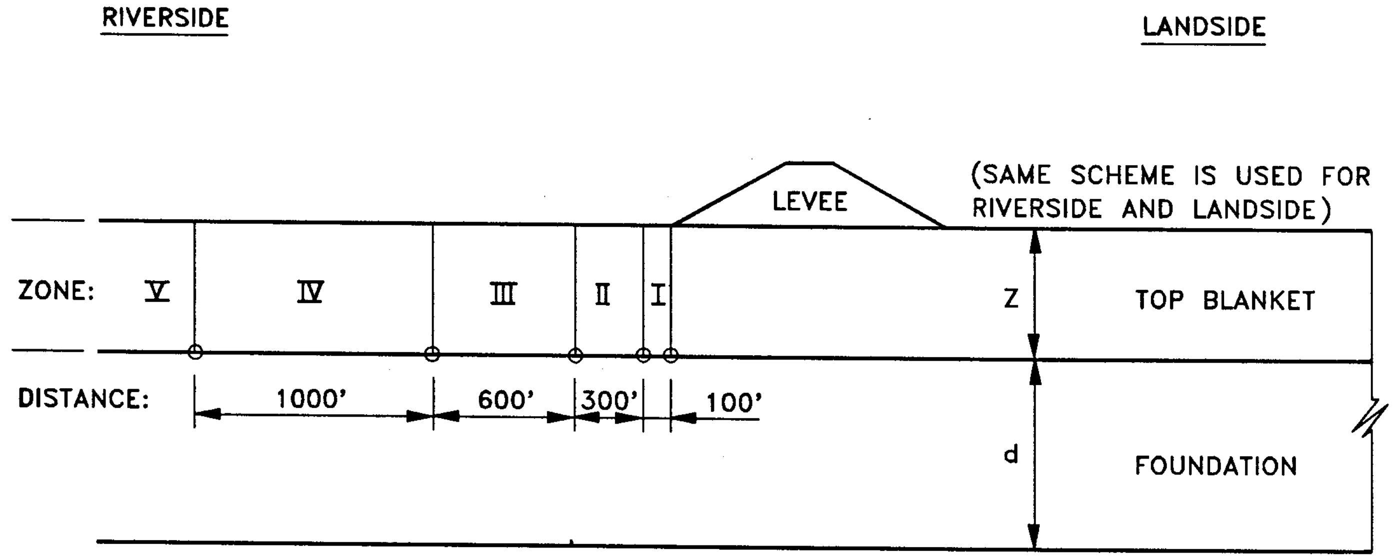
Capacity

The capacity of the program is determined by the size of the variables in the DIMENSION statements. Currently, the storage required for the sum of the code, data, and constants blocks is about 200 Kbytes. The maximum number of nodes corresponding to this capacity is 300. Increasing the dimensions of the variables in the DIMENSION statement can increase the capacity. However, the memory limitations of the computer system will be the controlling factor of the extent to which the capacity can be increased. Also, it should be noted that as the number of elements used in the analysis gets larger, the computational time gets longer.

Because of the program size, it is recommended to always clear all system memory, disk controller buffers, and keyboard buffers before the program is run. The user must first turn the computer off and then turn it on again. Different computer systems will have different commands for clearing the system memory (for example, in PC compatible systems press down **Ctrl**, **Alt**, and **Del** keys to clear the memory and "reboot" up the system).

Dimensions

According to the program capacity, the maximum number of nodes that can be generated is 300. As previously discussed, LEVEEMSU always models open entrance and exit conditions at the first and last specified vertical sections. Infinitely long entrance (L_1) or exit (L_3) distances must be approximated by the user specifying the beginning or ending sections at very large distances from the levee. A variable node spacing scheme is implemented in the computer program. Near the levee toes, smaller spacing is generated by the program. As distances increase away from the toes, this node spacing is increased according to the scheme shown in Figure 23. The same node generation schemes is used for both riverside and landside domains. Also, the same scheme is implemented in both the two-layer and three-layer models. The analyses models in LEVEEMSU require the specification of top blanket. This program cannot be used if the subsurface profile is uniform such that no top blanket is present. In this case, flow net or other analysis method should be used.



ZONE	NODE SPACING
I	dx*
II	2dx
III	4 dx
IV	8 dx
V	20 dx

NOTE: dx* = MINIMUM NODE SPACING AS SPECIFIED BY THE USER.

Figure 23. Node generation scheme

6 Analysis of Prototype Levee Reaches

Two levee reaches were selected for analysis as case studies to demonstrate the application of the two-layer and three-layer models. These reaches were identified as having sufficient data to conduct the analysis with foundation conditions appropriate for program application. The two case studies are:

a. Huntington District, Magnolia Levee; site location map is presented in Figure 24: Two-Layer Foundation.

b. Rock Island District, Sny Island "F"; site location map is presented in Figure 25: Three-Layer Foundation.

Huntington District, Magnolia Levee

Site description

The Magnolia levee drainage district is located in the Muskingum watershed of southeastern Ohio. The levee is located 6.5 miles east of Bolivar dam on Sandy Creek of the Tuscarawas River, a tributary of the Muskingum River. The levee protects the town of Magnolia, Ohio. The total length of the levee is 4,877 ft with crest elevations that vary between el 966 and 976.[1] The levee is monitored by thirteen open tube piezometers that are strategically located along the length of the embankment. The levee has no relief wells.

Soil conditions

Soil profiles for the site are shown in Figures 26, 27, and 28 with location of these sections presented in Figure 29. The site is generally underlain by cohesionless soils that mainly consist of fine to medium sand and gravel. A top stratum with a thickness that ranges from 4 to 8 ft and consists of silt and clay/sandy clay exists at the south reach of the levee east of the intake channel between sta 5+00 and 10+00. This layer is absent for the reminder of the levee site as may be inferred from sections presented in Figures 27 and 28.

[1] Elevations are in feet mean sea level.

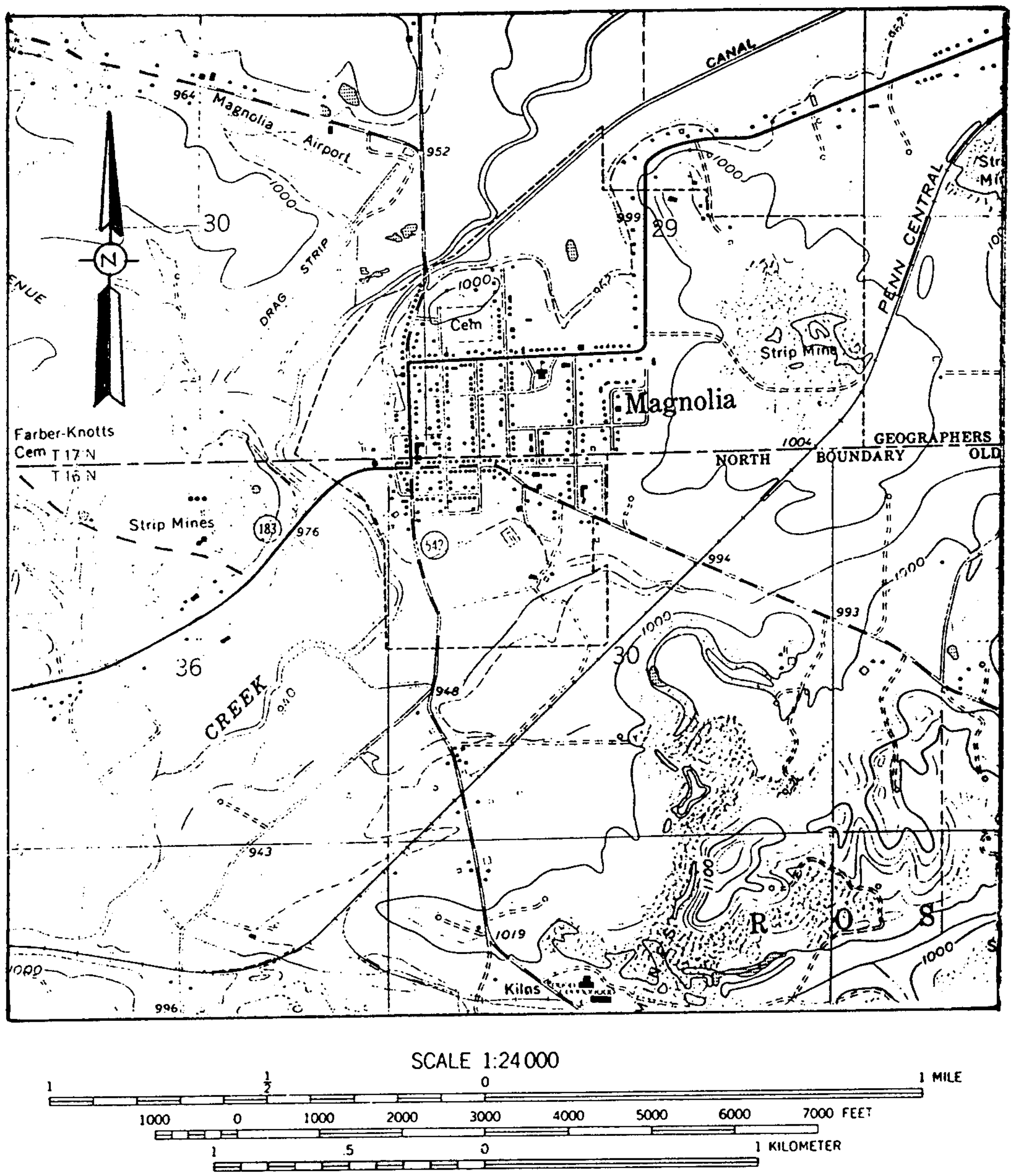


Figure 24. Site location map: Magnolia Levee, Huntington District

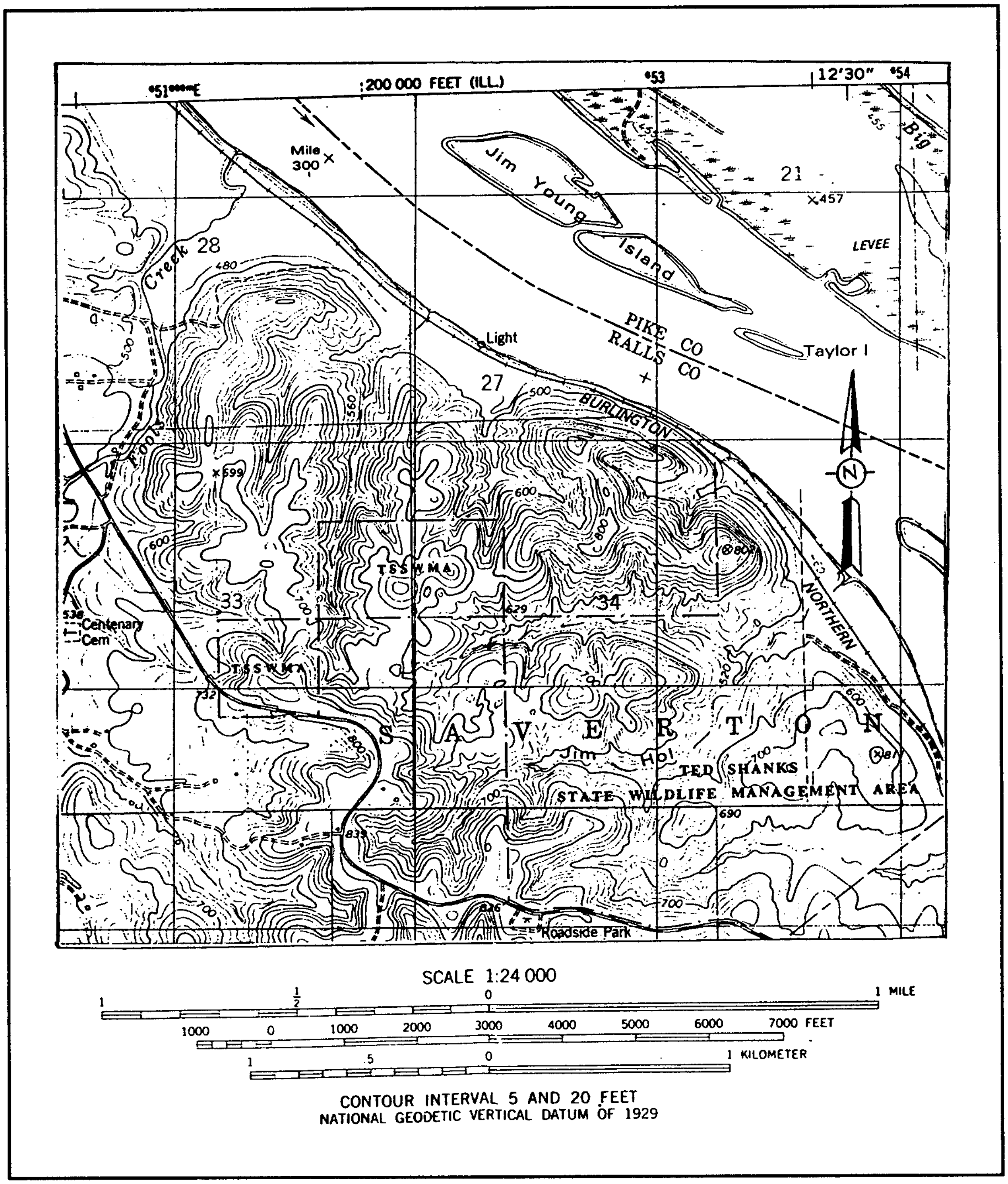


Figure 25. Site location map: Sny Island Levee, Rock Island District

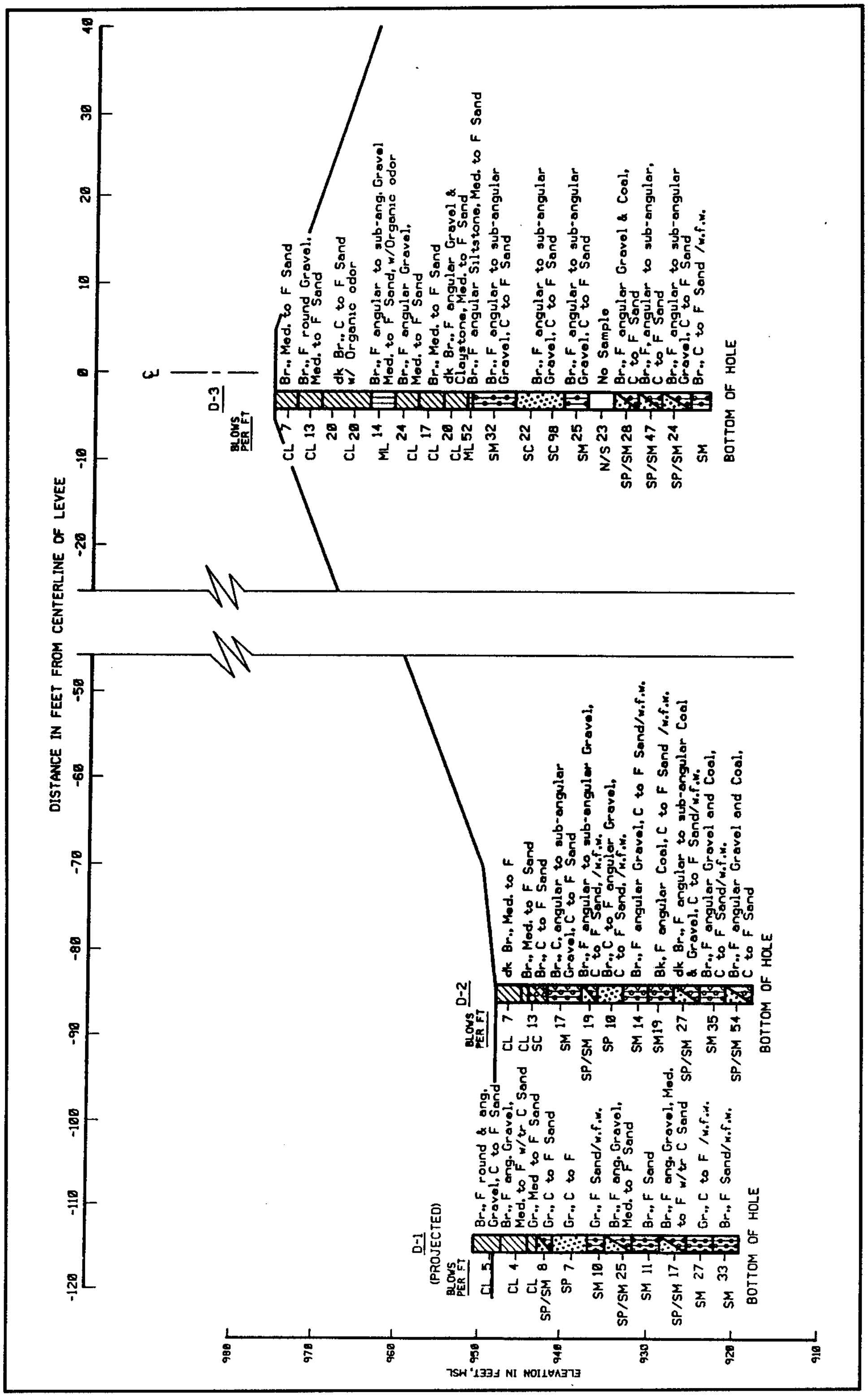


Figure 26. Soil profile between sta 5+00 and 10+00

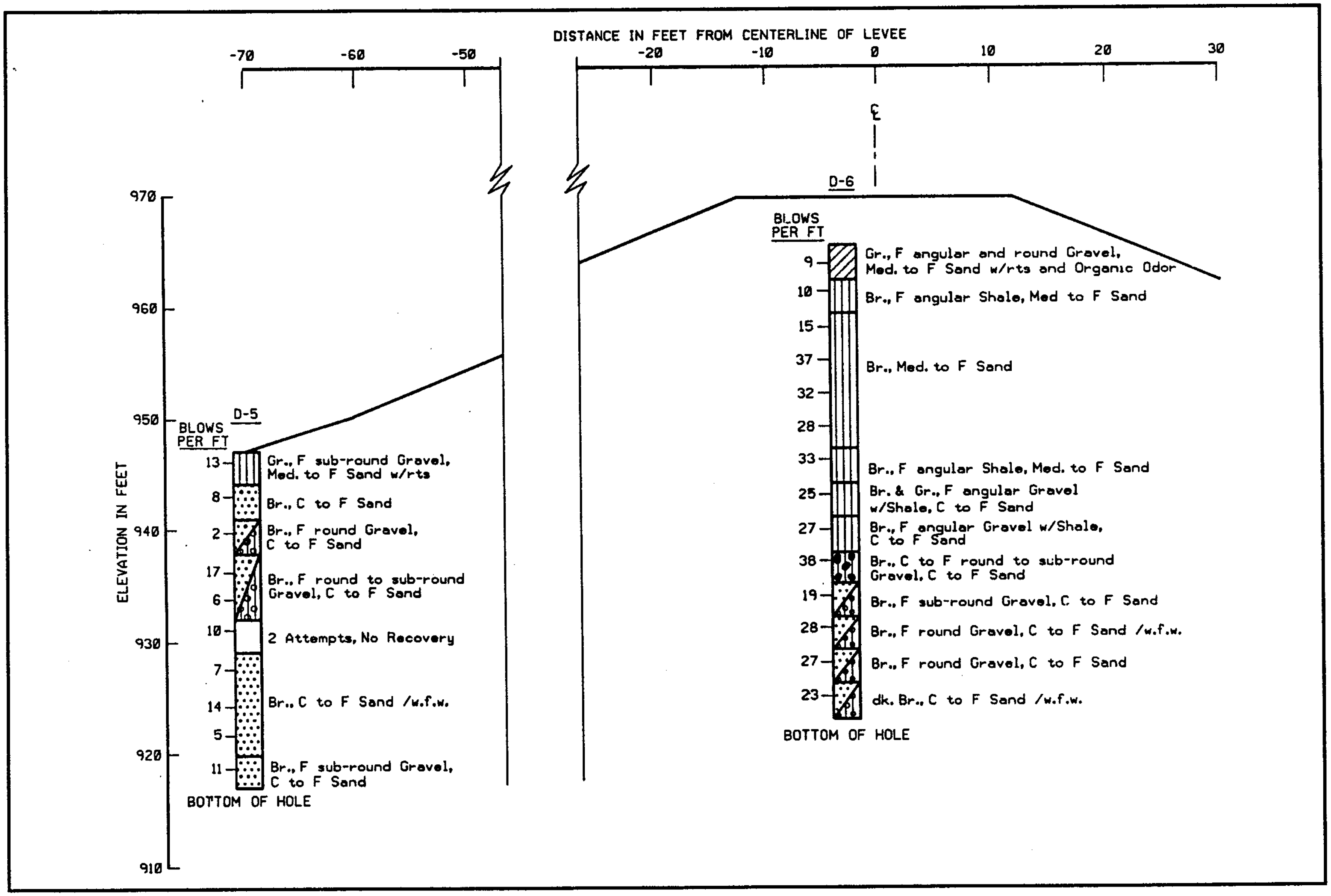


Figure 27. Soil profile between sta 20+00 and 25+00

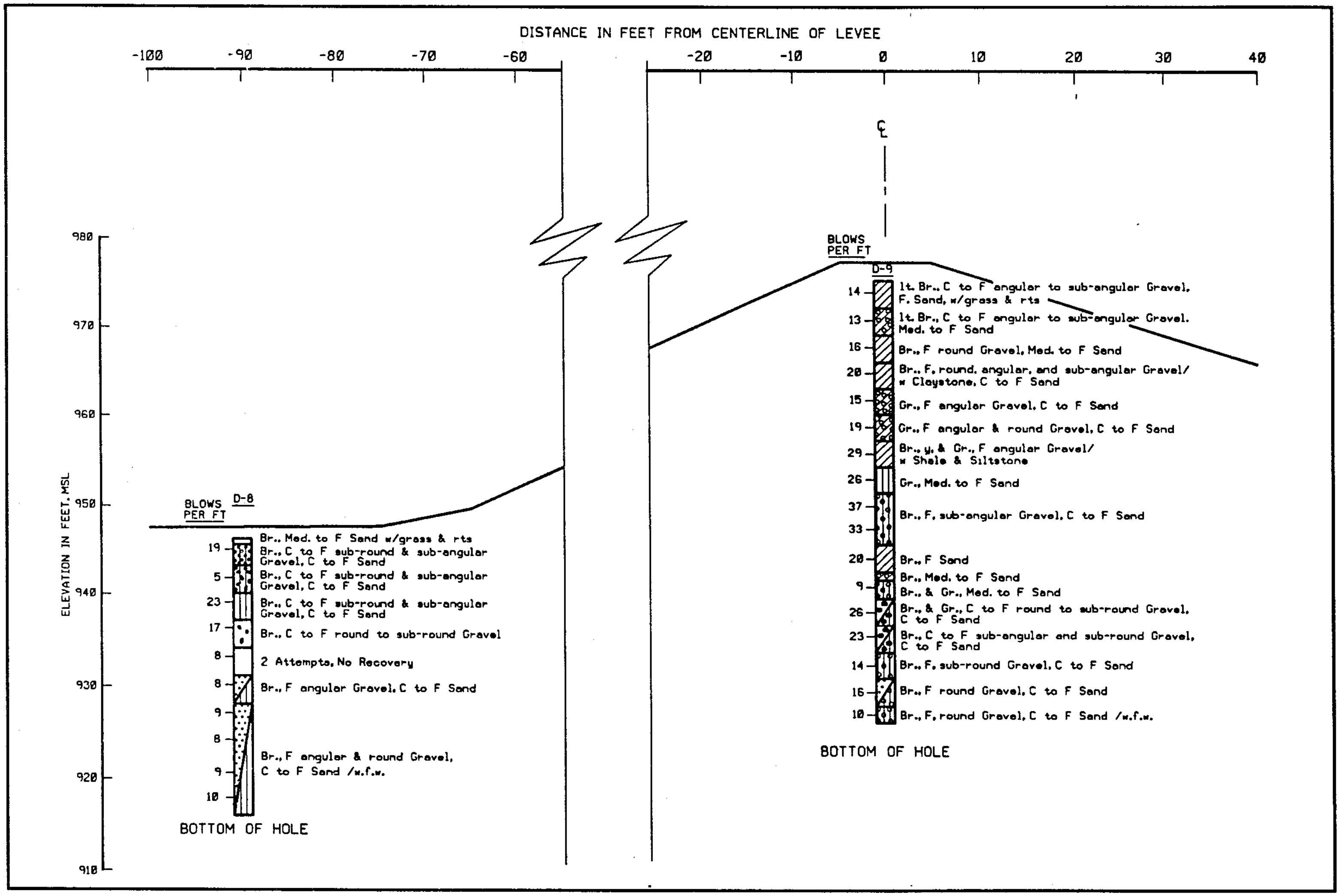


Figure 28. Soil profile between sta 40+00 and 45+00

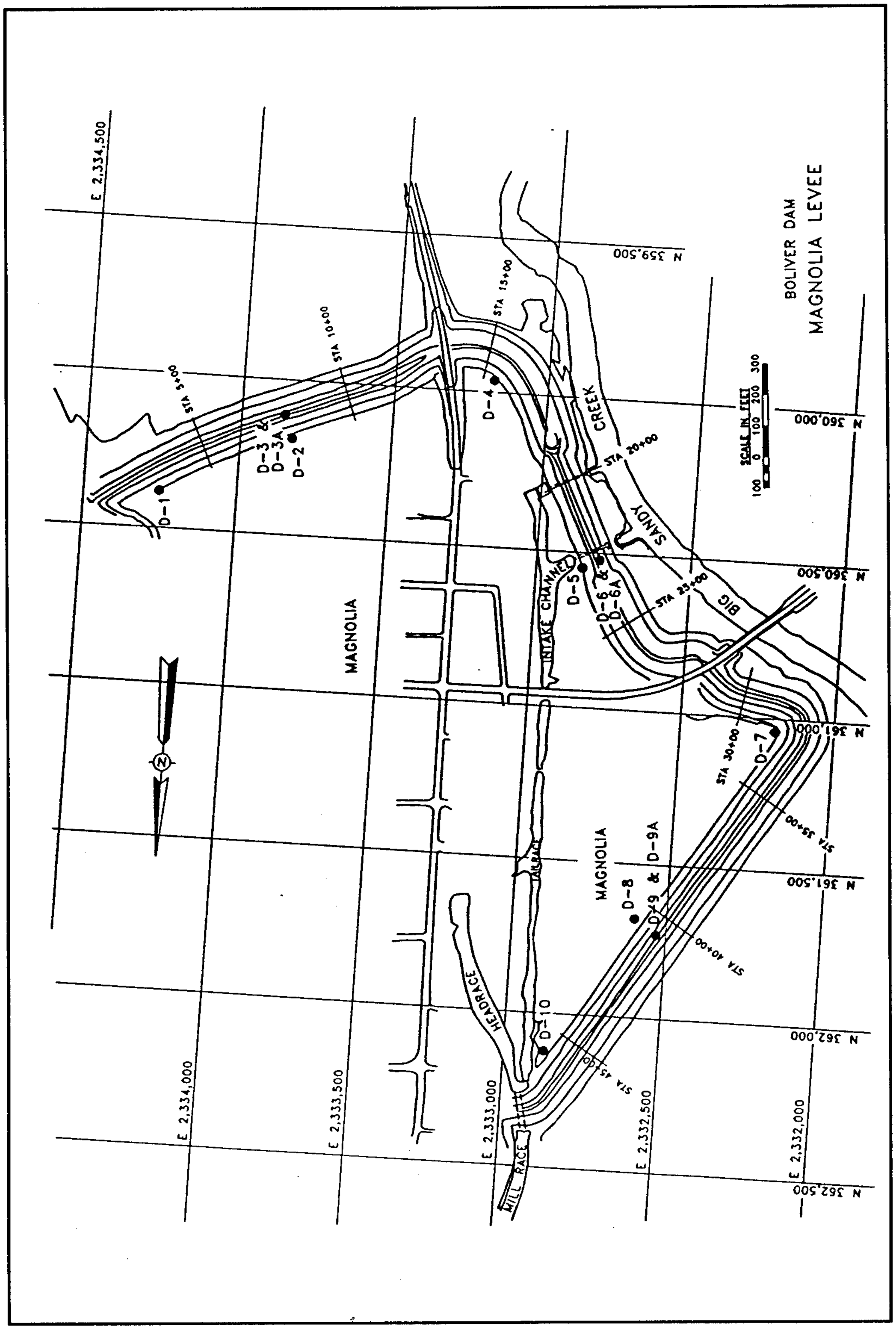


Figure 29. Soil borings and piezometers location plan - Magnolia Levee

Seepage conditions

Thirteen open tube piezometers (D-1 through D-10, D-3A, D-6A, and D-8A) are monitored to evaluate the pore water conditions in the foundation and embankment of the levee. These piezometers were installed in 1988. The tips of all piezometers were placed above el 931; therefore, the Pool of Record (P.O.R.) of 1991, which occurred at el 950.1, was the only event during which piezometric responses were observed. Approximately sixteen readings from each piezometer were obtained during this event as presented in the Periodic Inspection Report No. 5, June, 1991. In general, fluctuation in piezometer readings when no water is stored against the levee appears to reflect groundwater conditions. Data from piezometers monitored during the P.O.R. event and with an assumed tailwater elevation between el 943 and 944.7 are as follows:

Piezometer	Piezometer Elevation Date: 6/91
D-1	949.3
D-2	948.8
D-3	948.4
D-4	945.5
D-5	944.7
D-6	948.5
D-7	948.7
D-8	946.2
D-9	948.4
D-10	947.0

Analysis

Two cross sections were considered for the analysis of this site. The first cross section is between sta 5+00 and 10+00 in Figure 30 at the location of piezometers D-2, D-3, and D-3A and represents the portion of the site where a top blanket exists. The second cross section is between sta 20+00 and 25+00 in Figure 31 at the location of piezometers D-5, D-6, and D-6A and represents subsurface conditions with no top blanket. The idealized analyses sections and geometrical parameters are presented in Figures 30 and 31.
A typical input data file for one of the calculations is shown in Appendix D. The blanket permeability values were assumed to vary between 2x10-4 and 2x10-7 ft/min. The foundation permeability was assumed to be constant and equal to 2x10-2 ft/min.

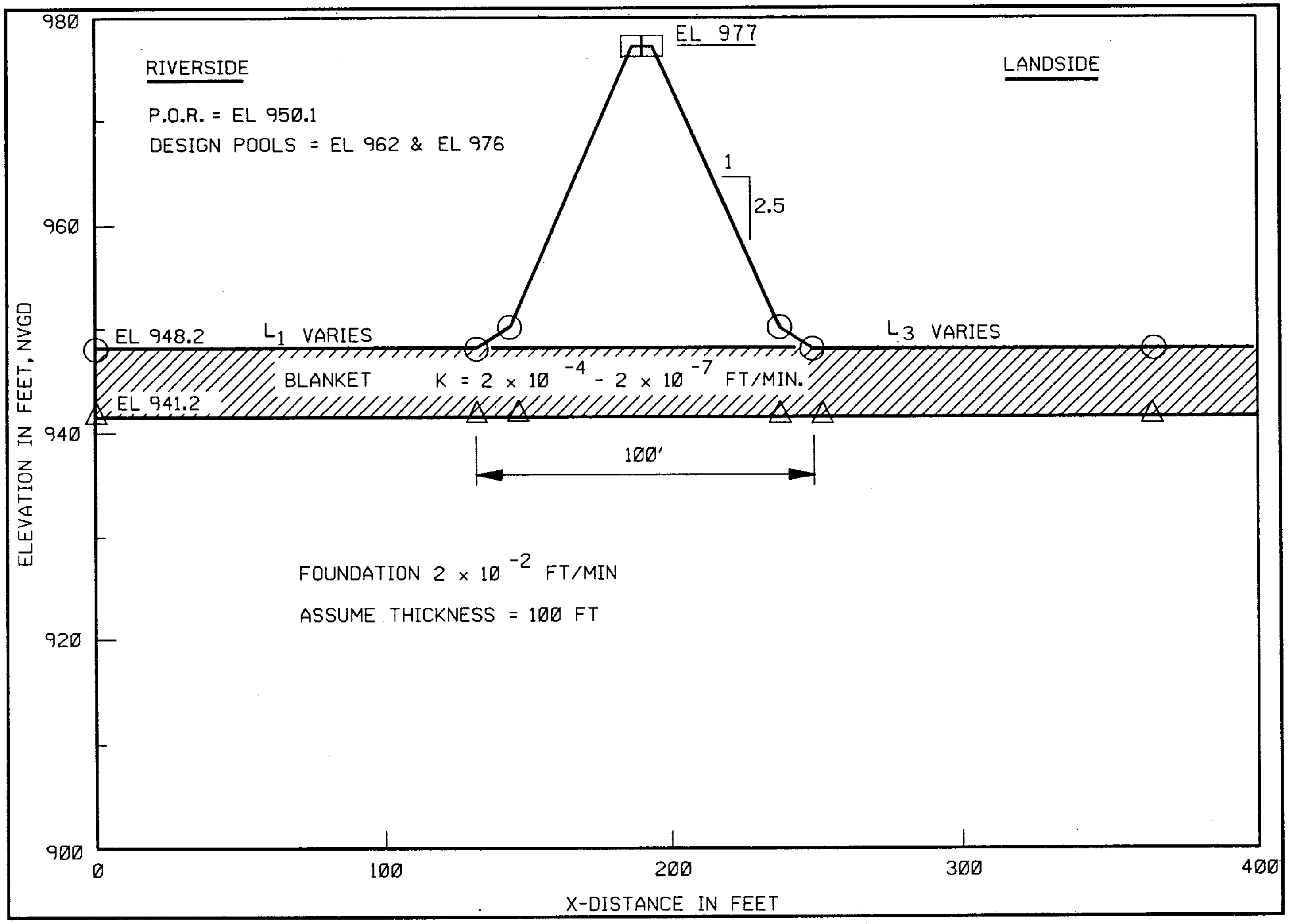


Figure 30. Magnolia Levee, Sandy Creek - idealized section between sta 5+00 and 10+00

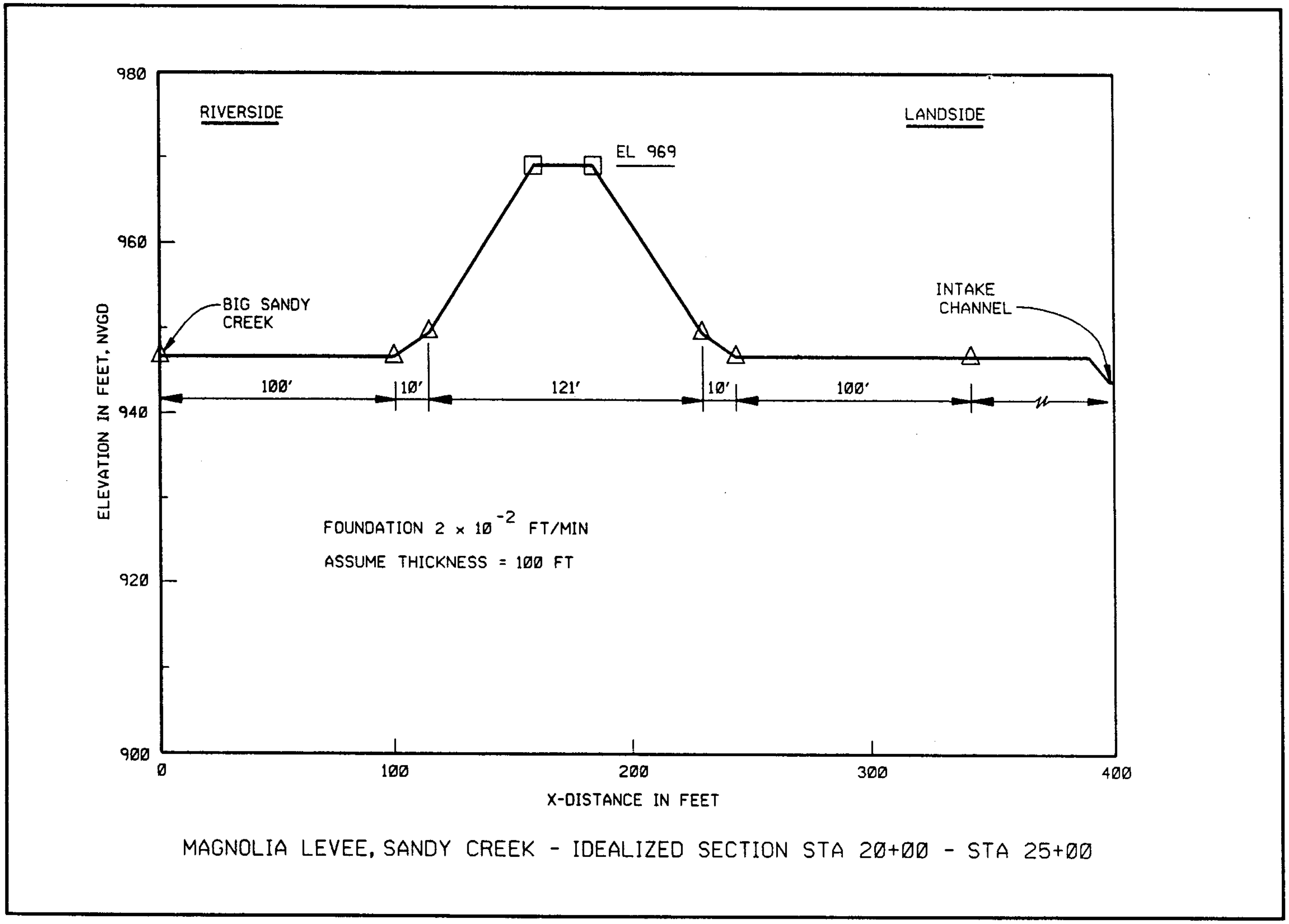


Figure 31. Magnolia Levee, Sandy Creek - idealized section between sta 20+00 and 25+00

Results and Discussion

Results of the analysis for the first cross section are presented in Figures 32 and 33 as a function of the permeability ratio k_b/k_f. The estimated exit hydraulic gradient varied as a function of the assumed blanket length on the riverside and landside. In the case of blanket length equal to 2,000 ft on the riverside and 175 ft on the landside, the value of the exit hydraulic gradient decreased as the permeability ratio (k_b/k_f) is increased. For a river pool of el 976 and permeability ratio of 100, the exit hydraulic gradient was on the order of 1.1. As the permeability ratio is increased to 100,000 and the permeability of the top blanket is decreased, the exit gradient was reduced to a value of approximately 0.4. On the other hand with a blanket length of 200 ft on the riverside and 1,750 ft on the landside assumed, the value of the exit hydraulic gradient increased as the permeability ratio is increased, as shown in Figure 33. In case of a river pool elevation of 976, the value of the exit hydraulic gradient ranged from approximately 1.5 for a permeability ratio of 100 to 3.5 for a permeability ratio of 100,000. It is of interest to note that for different pool elevations, the variation in the value of the exit hydraulic gradient was slight in the case of a blanket length equal to 200 ft on the riverside and 1,750 ft on the landside. Such observation emphasize the importance of accurate characterization of the blanket geometrical and hydraulic conditions.

Compared to piezometer D-1 and D-2 readings of el 949.3 and 948.8, analysis from different permeability ratios predicted an average piezometric head of el 949. This piezometric elevation was predicted for a river pool of el 950.1 based on the fact that the pool elevation on the landside coincided with the ground surface.

The use of LEVEEMSU is not proper for the analysis of the second cross section, where no top blanket is present. As indicated in EM 1110-2-1913, the construction of a flow net is required for the analysis in such a situation. Results from flow net indicated an exit hydraulic gradient of approximately 1.0 with a river pool of el 969, a homogenous foundation layer, and an impermeable levee.

In general, analyses results indicated that potential problems could occur at the levee under higher pool elevation than have occurred to date. Predicted exit hydraulic gradients for the two sections analyzed are generally above critical and therefore indicate a high probability of piping and boiling to occur in cases where river elevations exceed el 962. Boiling may be specially critical where no, or relatively thin, top blanket is present to provide seepage resistance.

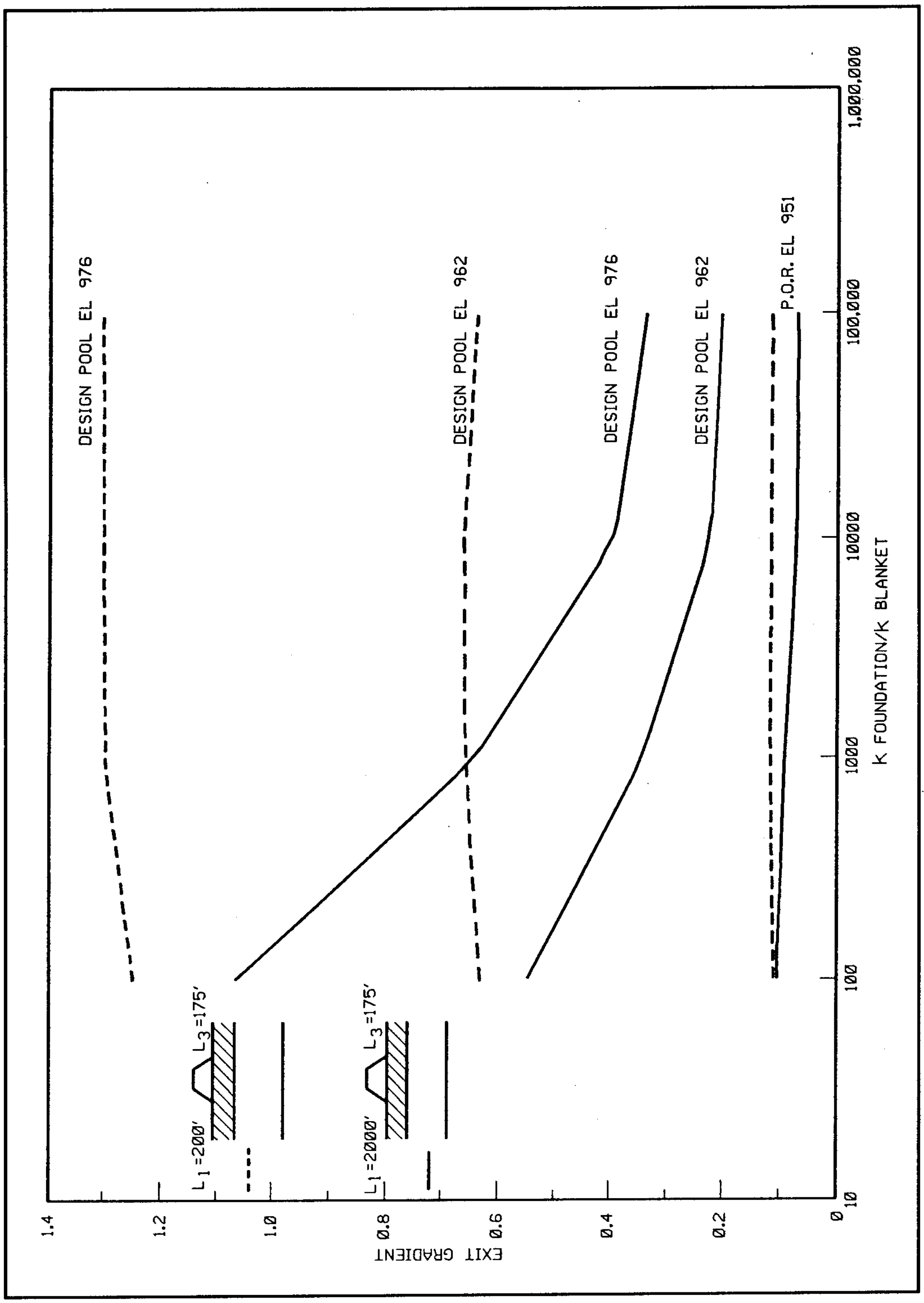


Figure 32. Variation of exit gradient with permeability ratio - decreasing trend

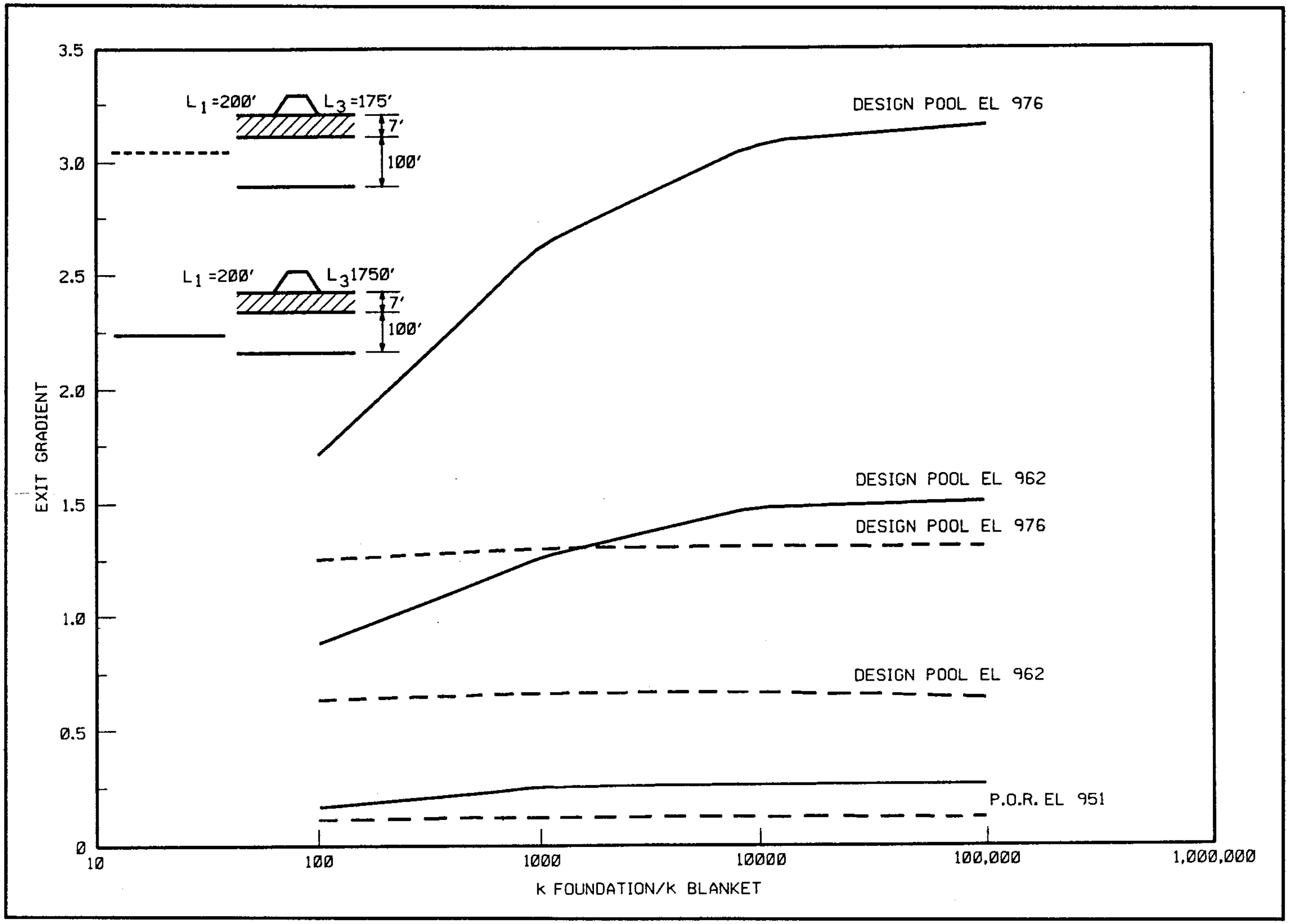


Figure 33. Variation of exit gradient with permeability ratio - increasing trend

Rock Island District, Sny Island "F"

Site description

The Sny Island Levee Drainage District is located on the east bank of the Mississippi River downstream from Quincy, Illinois. Six piezometer ranges A, F, B, G, H, and I were established in the period between 1950 and 1954 within the pool areas of Locks and Dams 22 and 24. Data used in the analysis presented herein are from piezometer range F.

Range F is located at levee sta 886+17 on the slack side of the river at river mile 300.1. This range site was established in November 1954. The current levee crest elevation is 472.8 with average ground surface elevation at the levee toe of approximately 458.6.

Soil conditions

Soil profile for the site is shown in Figure 34. The top stratum thickness ranges from 4.8 to 10 ft and generally consists of 2 to 4 ft of lean clay overlying silt and silty sand. The bedrock is of the Ordovician formation and the bedrock elevation at this site is significantly higher compared to the regional elevations. Therefore, the thickness of the pervious stratum at this location is approximately 34 ft compared to 100 ft elsewhere.

Seepage conditions

As described by Cunny (1980), seepage problems have been reported since the installation of the piezometers. These problems included toe seepage, sand boils, and pin boils in 1960 when the river crested at el 462.5, pin boils in 1965 when the river crested at el 468.8, and light toe seepage in 1973 when the river crested at el 474.2. It was noted by Wolff (1989) that the less severe problem observed for the highest river stage may be attributed to the fact that the levee was enlarged between 1965 and 1967 with the addition of a berm that increased the length of the effective base width. Data from five open tube piezometers (F-1 through F-5) monitored between the period of 1960 and 1965 are as follows:

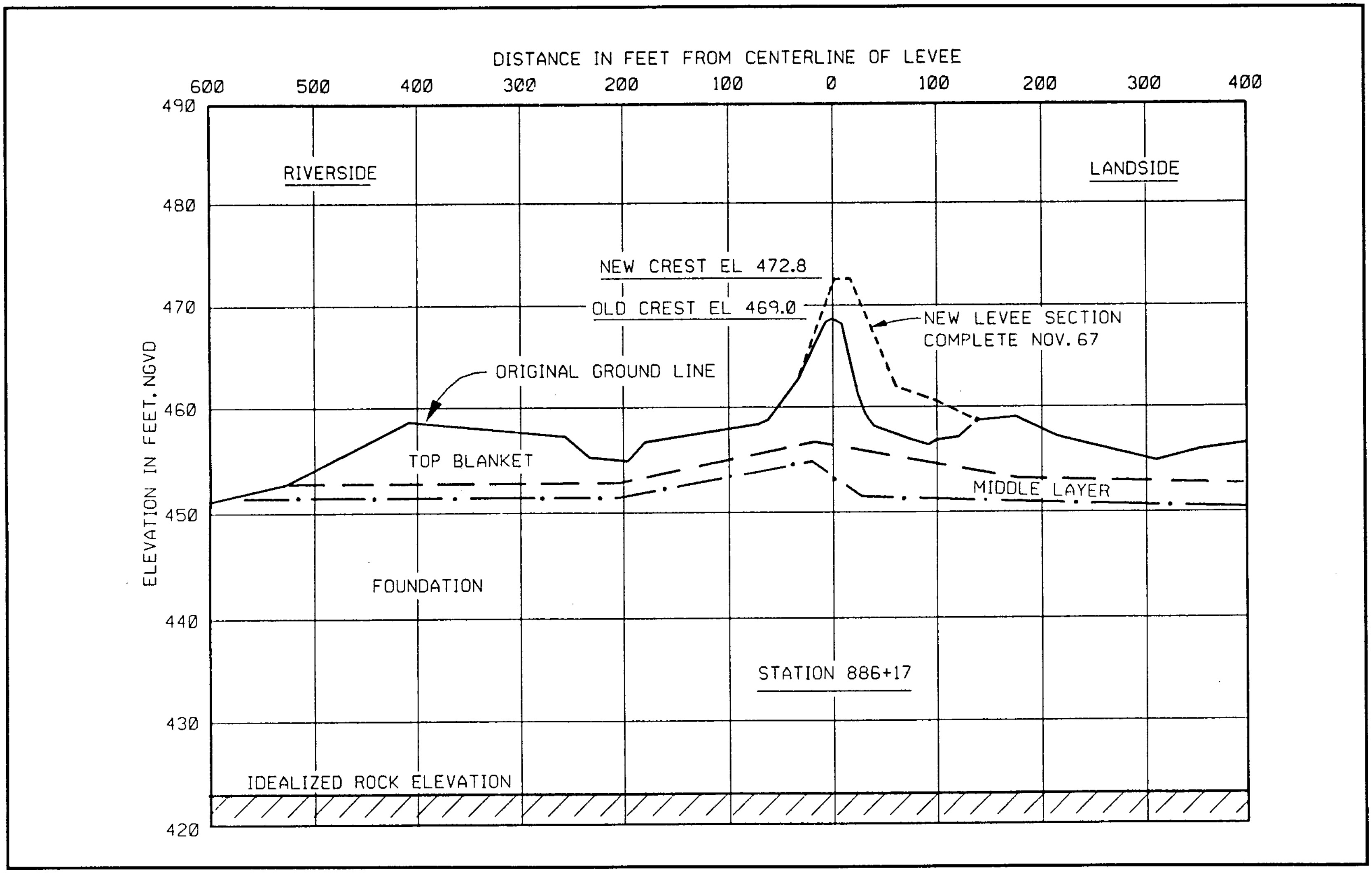


Figure 34. Subsurface soil profile, Sny Island - Range F

Table 1 Piezometer Number and Location					
Date	River Stage	F-1 10 ft Riverside of Levee Center Line	F-2 30 ft Landside of Levee Center Line	F-3 180 ft Landside of Levee Center Line	F-4 330 ft Landside of Levee Center Line
4/1/60	463.76	460.91	460.08	458.44	456.03
4/5/60	465.35	461.71	460.60	458.88	456.29
4/8/60	467.07	462.60	461.07	459.34	456.36
4/6/61	463.05	460.49	459.73	458.27	455.95
3/22/62	462.09	460.03	459.32	458.01	456.03
3/2/65	467.78	463.43	461.69	459.37	456.38

Analysis

Data at this piezometer range have previously been analyzed by Cunny (1980) and Wolff (1987). The idealized analysis cross section is shown in Figure 35. Irregularities in the profile include an irregular ditch approximately 200 ft riverside from the center line of the levee and a top blanket of variable thickness as shown in Figure 35.

The soil and geometric properties utilized in the analysis were obtained from studies performed by Wolff (1989) and Cunny (1980) and are as follows:

L_1 = 510 ft L_2 = 100 ft L_3 = 400 ft
k_b = 0.0002 ft/min k_f = 0.2 ft/min
kmv = 0.01 ft/min kmh = 0.04 ft/min

These values were selected such that a reasonable agreement was obtained between predicted and measured piezometric data when conventional analysis and the computer program LEVEE3L were used to perform these predictions. The exit distance of L_3 = 400 ft was selected based on the sluggish response of F-4 which suggested that most of the seepage was exiting relatively close to the levee. The analysis that was run utilized a minimum node spacing of 5 ft and a convergence tolerance of 0.00005 ft. The riverside and landside permeabilities of the top blanket were assumed not to vary with thickness. The landside water elevation was assumed to coincide with the ground surface elevation. A typical input data file for this case study is given in Appendix D.

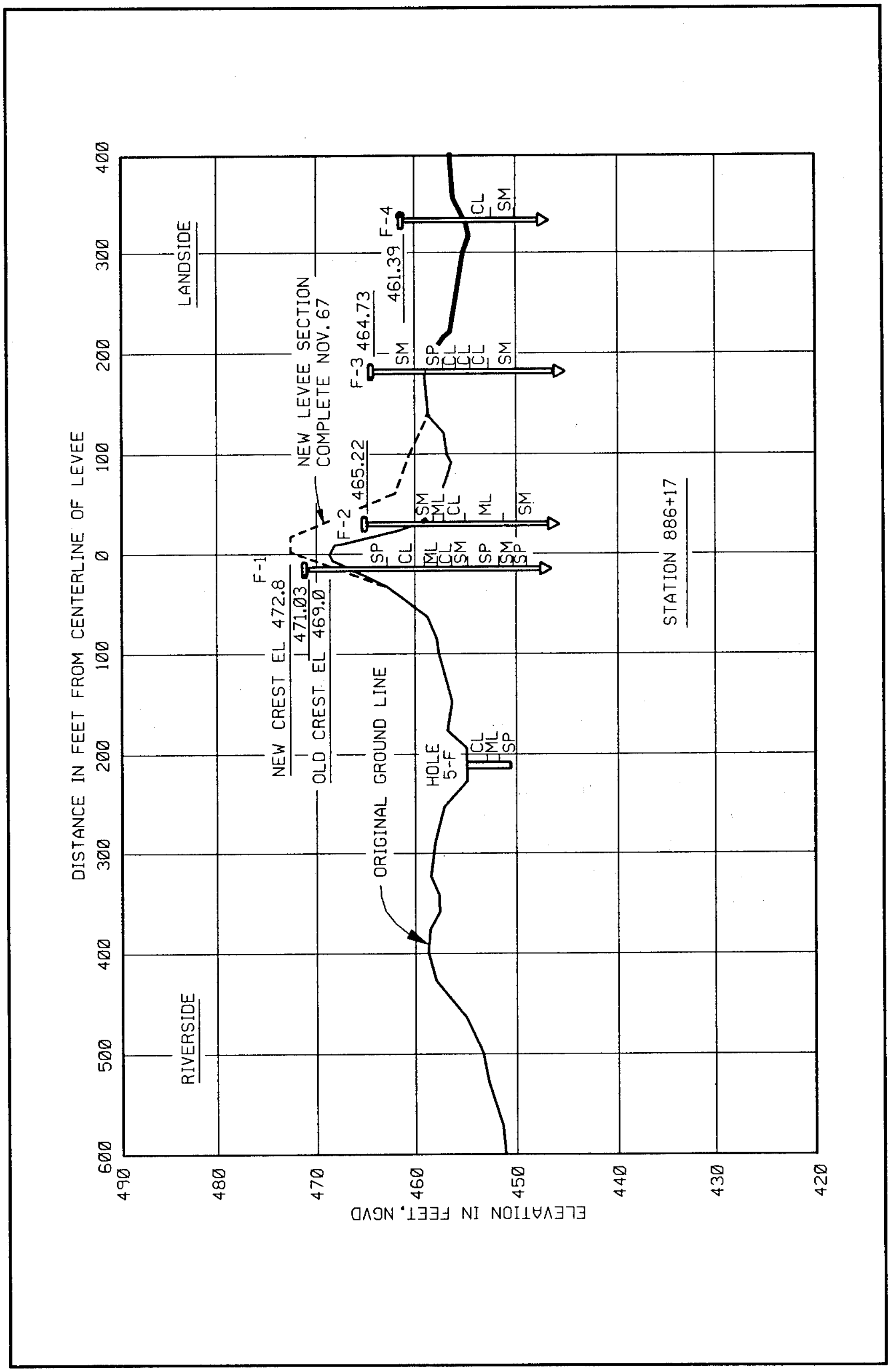


Figure 35. Idealized analysis profile, Sny Island - Range F

Results and discussion

Predicted and measured piezometric profiles are shown in Figures 36 and 37. Measured head at the location of piezometer F-4 practically remained the same for the different pool elevations and coincides with the ground surface elevation at this location. Such observation suggests that seepage exit is in the vicinity of the levee toe. In general, computed results tended to slightly overpredict the piezometric heads by approximately 10 to 25 percent with the most disagreement at the location of F-4. Exit gradients for the observed river stages were typically less than 0.2. However, maximum exit gradients occurred approximately 100 ft landward of the levee toe at the depression area shown in Figure 34. The following table presents the value of the maximum exit gradients for the analysis conditions:

Table 2
Value of Maximum Exit Gradients

Permeability Values ft/min	Gradient	4/1/60 Pool el 463.67	4/5/60 Pool el 467.07	4/8/60 Pool el 463.05	3/22/60 Pool el 462.09	3/2/65 Pool el 467.78
kmhl=0.04 kmvl=0.001 k_b=0.0002 k_f=0.2	i(max)	1.27	1.45	1.63	1.12	1.71

The permeability of the middle layer is assumed to be uniform, and therefore the landside and riverside values are equal. In this case, predicted gradient values ranged from 1.1 to 1.7. These values exceed critical gradients and therefore indicate probable heavy seepage and boiling at the location of the depression area.

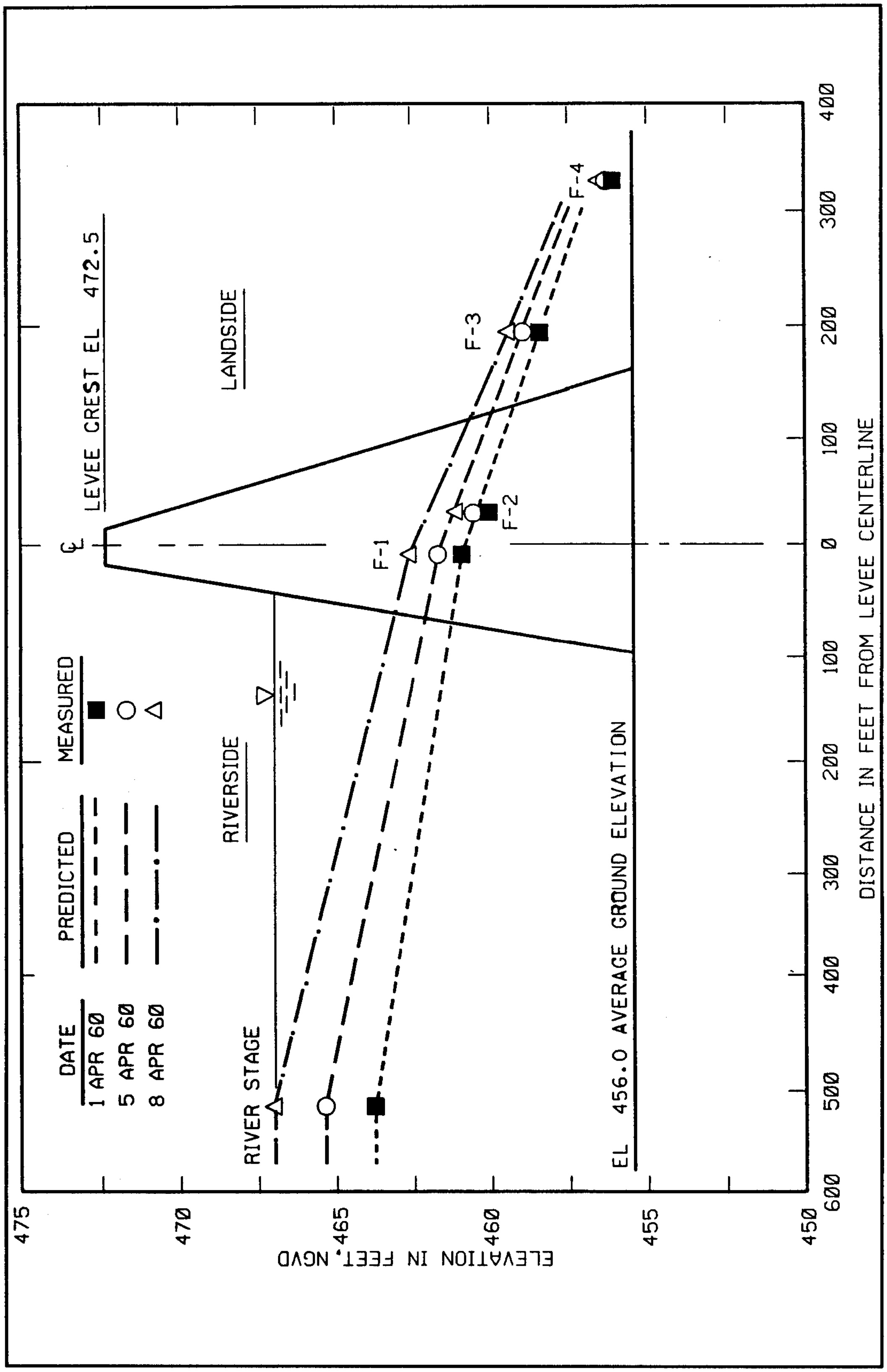


Figure 36. Predicted versus measured response, Sny Island - Range F (1, 5, and 8 Apr 60)

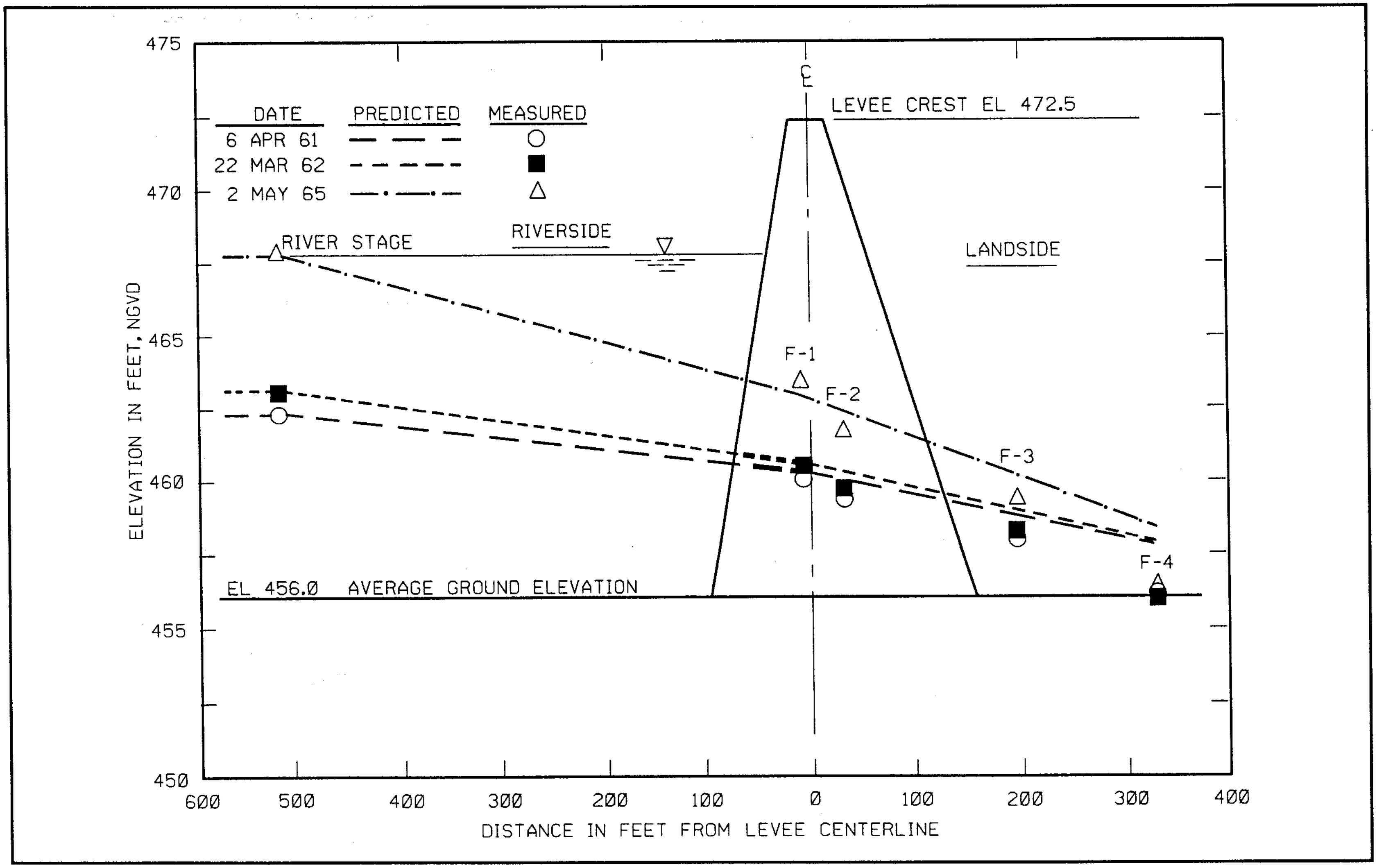


Figure 37. Predicted versus measured response, Sny Island - Range F (6 Apr 61, 22 Mar 62, 2 May 65)

7 Applications

The computer program LEVEEMSU can be used for the preliminary design of underseepage control measures such as seepage berms and relief wells. In the case of seepage berms, the exit hydraulic gradient is decreased through the increase of the distance over which head drop occurs. Berm thickness and width are specified by the user. In the case of relief wells, the pressure gradient is dissipated by the intercepting wells; therefore the hydraulic gradient is decreased. Piezometric heads at the relief wells are specified by the user, and the amount of discharge to maintain this head at the well location is computed by the program.

Design of Seepage Berms

To illustrate the design process of seepage berms, a semipervious berm is assumed to have a vertical permeability or permeability curve number equal to that of the landside top blanket. The berm is modeled by an adjustment to the geometry of the landside blanket to include the berm. In general, when trial and error adjustments are used, a designer can size a berm that will result in any desired gradient at any landside location. Figure 38 illustrates a copy of the screen display for an input file entitled DATABERM. This file was developed by adjusting the geometry of file DATACHK to include a 300-ft-long berm with a thickness of 5 ft at the levee toe and 2 ft at the berm toe. The maximum gradient of 0.71 occurs at the berm toe (x = 2,106). From the printed output file, the gradient at the levee toe and any other location can be obtained. Furthermore, the graphic display of the piezometric line in relation to the berm surface provides the designer with basis for making trial and error adjustments of berm geometry.

Design of Relief Wells

As previously discussed in Chapter 3, use of the option to specify piezometric head at one node allows approximate modeling of a well line and provides the designer with a relationship between average piezometric elevation at the well line and well flow per unit length of levee. These results provide data for preliminary studies and cost estimates where only the approximate number of wells required to maintain the piezometric head, at the

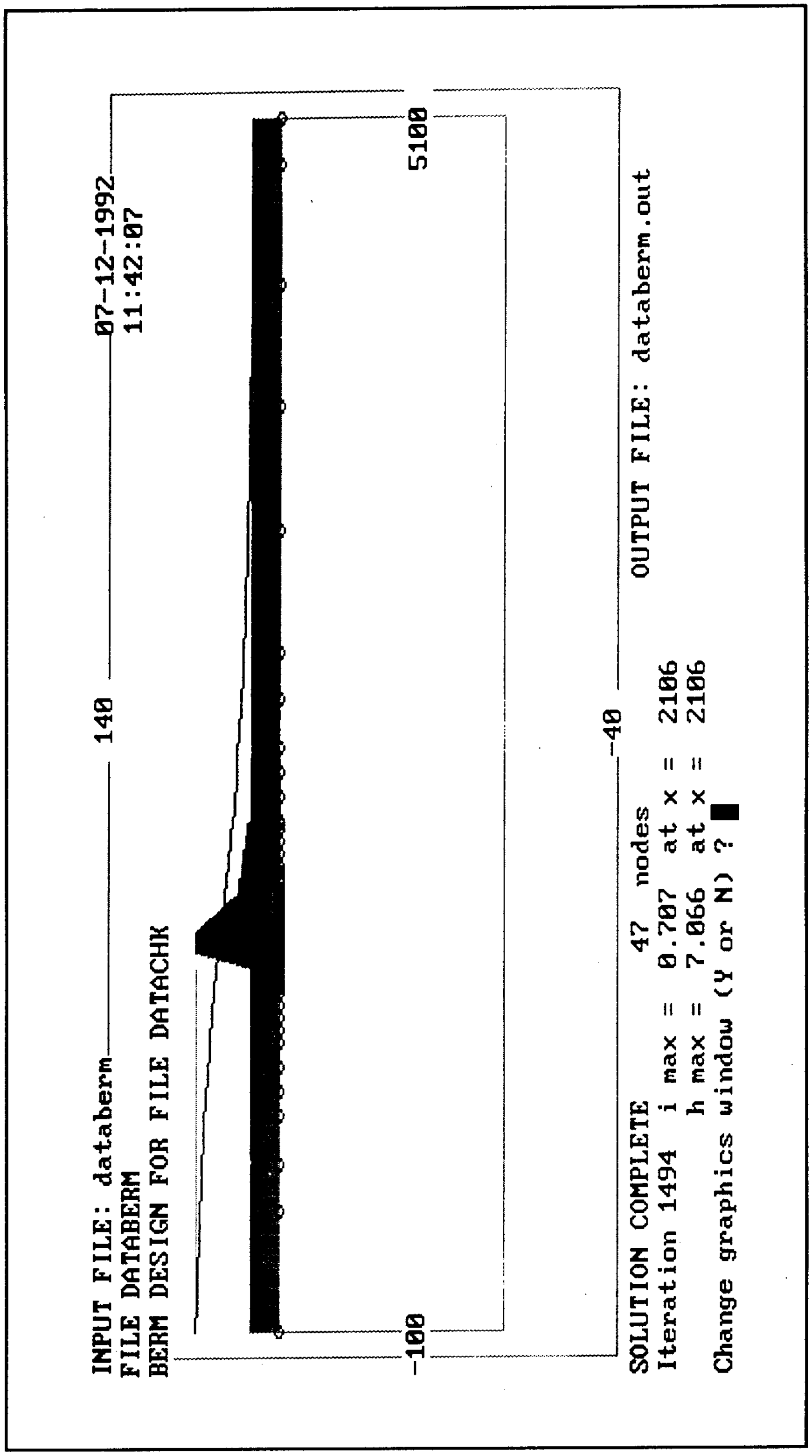


Figure 38. Copy of screen output, file DATABERM

specified location, is estimated. Detailed design of a well system including dimensions, spacing, hydraulic losses, and partial penetration effects is beyond the scope of this computer program.

8 Summary, Conclusions, and Recommendations

Summary

Analysis software, LEVEEMSU, for evaluation of levee underseepage is presented with a description of capabilities and limitations. The computer program incorporates models to analyze underseepage for levee profiles characterized by two-layer and three-layer foundation. Analysis models implemented in LEVEEMSU were developed based on simplified finite difference formulation. Key analysis parameters to be used as input for the program include geometry of the top blanket, pervious substratum, and landside and riverside pool elevations. Profile geometry can be either irregular or uniform. Blanket permeability may be constant or vary as a function of blanket thickness. To calculate the residual head along the entire length of the top blanket, a finite different approximation of Bennett's equation is used. Several parameter studies were performed to demonstrate the program capabilities. These studies included analysis of levee sections having ditches and borrow pits. Two prototype reaches were analyzed to assess and demonstrate the program's applicability. These reaches included Magnolia Levee, Huntington District, and Sny Island Levee, Rock Island District. The Magnolia Levee served as a case study for a two-layer foundation system, and Sny Island Levee served as a case study for a three-layer foundation system. Several predictions were made from idealized geometries and estimated soil parameters. Predictions were compared with actual measurements, and results indicated the suitability of the developed model to predict the underseepage behavior.

Conclusions

Based on the results presented in this report, the following conclusions can be advanced:

a. The program is relatively simple and can be run on IBM compatible microcomputer under the MS DOS (TM) operating system having CGA or EGA graphics capabilities.

b. The analysis models are developed based on assumptions similar to those commonly followed in conventional analysis. Therefore, program solutions should allow the user to match conventional analyses and then extend them to more complex conditions.

c. Results from the implemented model seem to be reasonable. To verify the two-layer model, hand solutions were used for cases of uniform geometry where conventional solutions can be obtained. To verify the three-layer model, the middle layer of the foundation was collapsed such that results can be compared to those from the two-layer model. Good agreement observed between results from the two-layer model confirms the applicability of the three-layer model.

d. In general, parameter studies show that the program exhibits consistent behavior when variable geometry and soil parameters are used. Also, the analysis model was applied to problems with ditches and relief wells.

e. Results of the case studies emphasized the importance of accurate characterization of the foundation sublayers. The length of the top blanket riverside and landside significantly impacts the predicted gradients.

f. LEVEEMSU provides a convenient analysis tool that should allow designers to approximately model actual field conditions. Prediction of exit gradients and hydraulic heads for the two case studies investigated reasonably matched measured data.

Flood protection is a complex system involving design, construction, maintenance, and performance evaluation of levees. The use of LEVEEMSU can provide flexibility in exploring the influence of changing key analysis parameters on the predicted results. Such a flexibility can lead to a reevaluation of design criteria with the benefit of reducing cost and improving safety.

Recommendations

Based on the results of this research, the following recommendations are made:

a. The program LEVEEMSU should be field tested by use in District offices, and the need for any corrections or improvements assessed.

b. To establish the limitation of LEVEEMSU, finite element analyses allowing through seepage and assuming anisotropic conditions should be conducted. Such analyses will provide information on the accuracy of the results from LEVEEMSU, with the simplified assumptions, as compared to those obtained from more rigorous analyses. Limitation

of LEVEEMSU through the use of variation of analysis geometry and key seepage parameters can be established.

c. The analysis algorithms implemented in LEVEEMSU can be modified to handle situations where transient conditions would control the hydraulic response. Transient analysis would be more appropriate in cases where drawdawn is anticipated to occur over a short period of time and in cases where the proximity of a ditch may not be influenced by duration of the high-water presence.

d. Analysis algorithms to handle infinite slope situations need to be developed. In infinite slope situations, the horizontal "only" flow in the pervious stratum will also have a vertical component. The governing mass balance equation can be adjusted to account for this component and its effect on the predicted hydraulic response.

e. The need for refining levee design criteria should be assessed. Many current criteria, such as dimensions, location of berms, and borrow pits and ditches, are arbitrary and conservative due to the lack of a rational analysis procedure.

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Appendix A
Data Input for LEVEEMSU

Creating Input Files in Batch Mode

Input data can be read from a standard ASCII text file created by a word processor or text editor. Information in the input file includes coordinates of the soil profile and information on material properties. Coordinate information is specified in terms of vertical sections cut through the profile. At each specified vertical section, the base of the pervious substratum, base of the top blanket, and ground surface are designated. For landside sections, the landside water surface is also designated. Layer boundaries are assumed to vary linearly between specified sections.

Example input files with corresponding variable names and definitions for two-layer and three-layer models are shown below. Graphical representation of these input files is presented in Figures A-1 and A-2, respectively.

<u>Two-Layer Model:</u> <u>Example Data File:</u>	<u>Variable Names</u>
IRREGULAR FOUNDATION	TITLE1$
TWO LAYER-TEST PROBLEM	TITLE2$
0.200	KF
2 "CONST" .0002 175	NRIVSECS PERMFLAGR$
PERMRIV YRIV	
750 60 140 158	X(1), Y1(1), Y2(1), Y3(1)
1750 60 140 160	"
4 "CONST" .0002	NLANDSECS PERMFLAGL
PERMLAND	
1900 60 140 160 160	X(*), Y1(*), Y2(*), Y3(*),
YWATER(*)	
2400 60 120 158 158	"
2800 62 140 155 158	"
4900 70 140 158 158	"
NO WELLS	WELLFLAG$

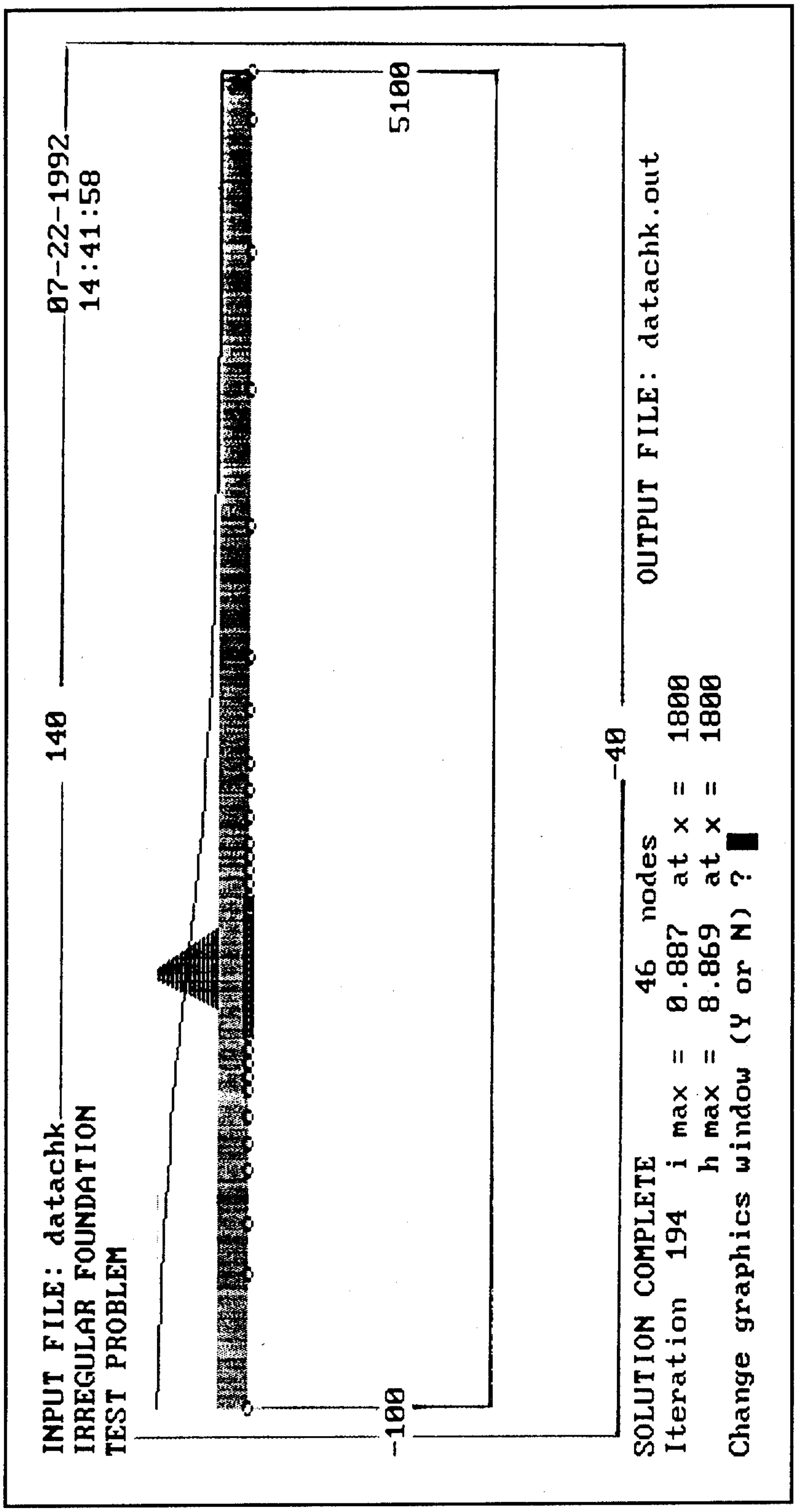


Figure A1. Copy of screen output, file DATACHK

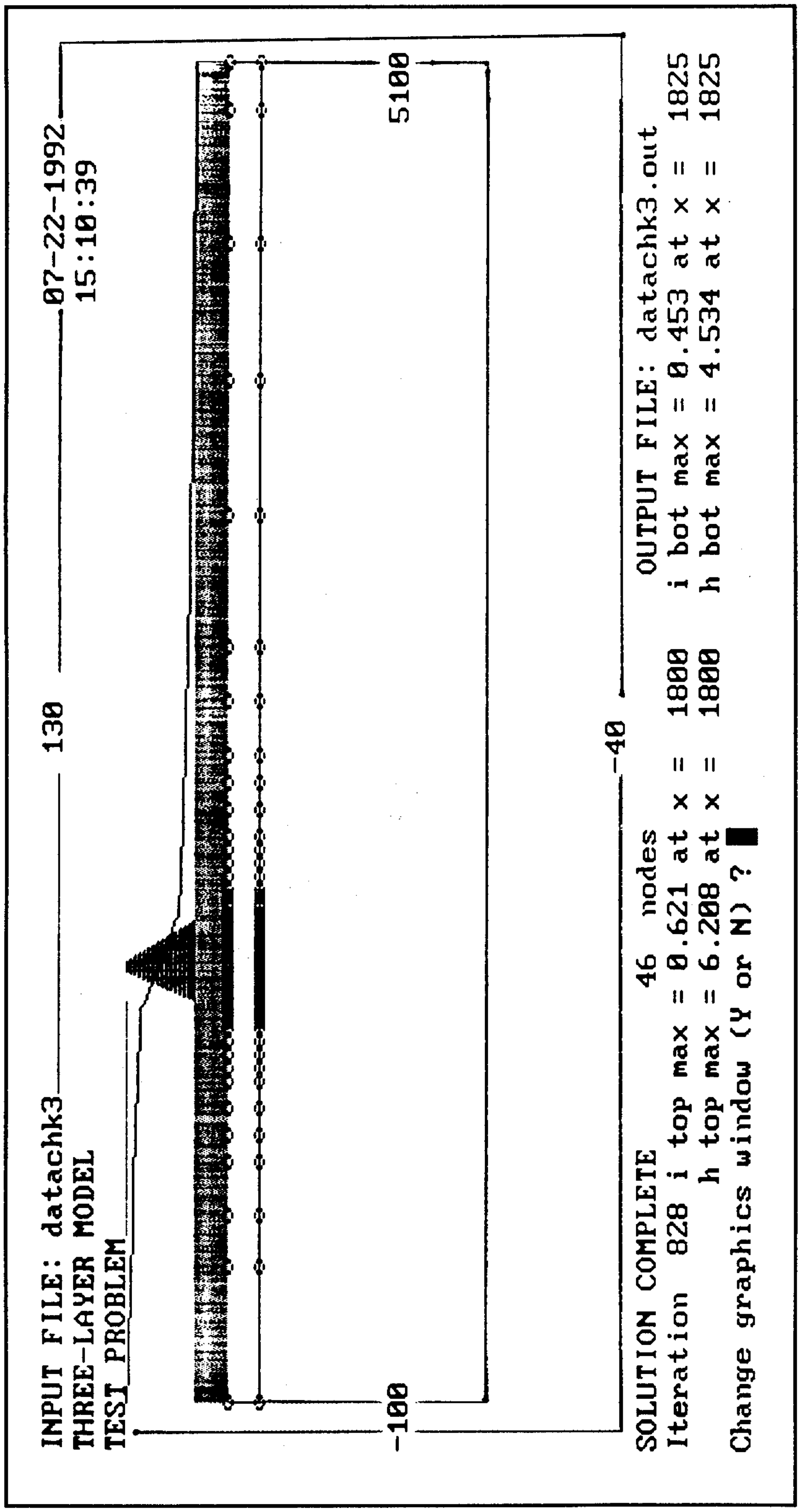


Figure A2. Copy of screen output, file DATACHK3

Three-Layer Model:
Example Data File:

Example Data File	Variable Names
IRREGULAR FOUNDATION	TITLE1$
THREE LAYER-TEST PROBLEM	TITLE2$
0.200	KF
0.0002 0.002	KMVR KMHR
2 "CONST" .0002 175	NRIVSECS PERMFLAGR$
PERMRIV YRIV	
0 0 70 80 90	X(1), Y1(1), Y2(1), Y3(1), Y4(1)
1150 0 70 80 90	"
0.0002 0.002	KMVR KMHR
2 "CONST" .0002	NLANDSECS PERMFLAGL
PERMLAND	
1800 0 70 80 90 90	X(*), Y1(*), Y2(*), Y3(*), Y4(*),YWATER(*)
5000 0 70 80 90 90	"
NO WELLS	WELLFLAG$

(If it is desired to model the effect of a line of relief well line, the last line above is deleted and two lines are added as shown below.)

.

.

WELL	WELLFLAG$
1920 162	XWELL YWELL

Creating Input Files in Interactive Mode

UNDER DEVELOPMENT

Appendix B
Running LEVEEMSU

LEVEEMSU is a stand-alone executable program compiled from a BASIC source code. The program runs on IBM compatible personal computers with the MS DOS operating system and CGA or EGA graphics capabilities. The program will not run on a system with a monochrome display. A math coprocessor is not required, but the program runs considerably faster if a coprocessor is installed. A graphics printer is required to obtain a plot of the foundation geometry and results.

Before the program is run, prepare and save one or more data files created for either a two-layer or three-layer problem in standard ASCII format with the use of a word processor or text editor. Format for data files is given in Appendix A and discussed in the report. Any number of files can be analyzed without exiting the program.

To obtain a printer plot of a CGA screen display, the DOS command GRAPHICS (program GRAPHICS,.COM) must be resident on the system and executed before the program is run. For example (User input is underlined):

C> <u>GRAPHICS</u>

To run the program, log to the drive where the program resides (usually drive C:) and type the program name:

C> <u>LEVEEMSU</u>

The program will display introductory information and ask what type of graphics display is available. Respond with:

<u>EGAC</u> or <u>CGA</u>

The option EGAC will provide a high resolution color graphic display of the problem. The option CGA will provide a medium-resolution color graphic display of the problem, suitable for copying to a graphics printer.

The program will ask for type of analysis model to run: type TWO for the two-layer model and THREE for the three-layer model. The program will

then prompt the user for the input file name. Enter the file name. Prefix the file name with the drive identifier and/or path, if different from the default drive and directory. Include the extension if present. For example: DATACHK, or A:DATACHK, or A:DATACHK.DAT are all valid data file identifiers. If the input file specified does not exist, the program will prompt for the file name again.

The program will ask for the output file name in a similar fashion. If the named file does not exist, it will be created. If it does exist, it will be overwritten.

The program will then ask the user if he wishes to change any of the default settings for closure tolerance, maximum iterations, and maximum node spacing near the levee toe. If he is satisfied with the present settings, he will press return for each value. If he wishes to change these values, he will type in the new value.

The program will print a summary of the user's input data. If he wishes a hard copy, he will press Shift-PrtSc before pressing Return to continue. Input data are also saved to a specified output file.

The program will provide a graphic display of the user's input data. If he wishes a hard copy, he will press Shift-PrtSc before pressing Return to continue.

The program will then solve for the head and gradient along the base of the blanket. When the solution is complete, it will plot the piezometric grade line. If the user wishes a hard copy, he will press Shift-PrtSc before pressing Return to continue.

The program will ask whether the graphics window is to be changed. This feature allows zooming in on a particular area of interest. Enter Y(es) or N(o) . If the response is yes, the program will display the coordinates of the current window and prompt the user for the new window coordinates. These coordinates are entered as minimum and maximum x and y values, respectively, separated by commas. The window boundaries can be changed as often as desired.

The program will ask whether the results are to be listed to the printer. Enter Y(es) or N(o) . Whether printed or not, results are saved in the output file for later printing using a word processor or the DOS COPY or PRINT commands.

The program will then prompt for a new problem. Enter Y(es) to go to a new problem, or N(o) to quit.

Appendix C
Example Run

```
          *********    LEVEEMSU    *********
                   LEVEE UNDERSEEPAGE
        *********     v 2.1 JAN 94     *********
-------------------------------------------------------------------------

               To Select Menus Use:  → arrow keys

|        INPUT          |CALCULATIONS| DISPLAY  |  OUTPUT/  |  SYSTEM  |
| 2 - LAYER | 3 - LAYER |            |  DATA    |  RESULTS  |          |

    @@@@

Options:
        Build (new 2-layer)          <<<  to select option
        Read (from disk)                  enter Highlighted letter
        Write (to disk)
        Edit (2-layer data)
        Print (2-layer data)
```

Figure C1. 2-Layer selection menu.

```
CONTROL MENU FOR DATA INPUT                 ↑y
                                            |
                                            └──→x

MAIN TITLE irregular foundation          SUB TITLE  test problem

HORIZONTAL PERMEABILITY PERVIOUS SUBSTRATUM .2

          RIVERSIDE DATA                            LANDSIDE DATA
          --------------                            --------------

NUMBER OF SECTIONS    2              NUMBER OF SECTIONS    2

PERM CALC METHOD      const          PERM CALC METHOD      const

TOP BLANKET VERT PERM .0002          TOP BLANKET VERT PERM .0002

WATER ELEV            110            WELL PRESENT  n0



                                                   <Esc> exit screen
```

Figure C2. Sample control menu input.

```
RIVERSIDE GEOMETRY DATA INPUT SCREEN        ↑y
                                            |
                                            └──→x
    X              Y1             Y2             Y3
----------     ----------     ----------     ----------

0              0              80             90

1500           0              80             90







 POINT NUMBER :   1
 SCREEN   1   OF   1
                                                   <Esc> exit screen
```

Figure C3. Sample riverside geometry data input.

```
                LANDSIDE GEOMETRY DATA INPUT SCREEN              ↑y
                                                                 |
                                                                 └──→x
     X            Y1          Y2          Y3          YWATER
 ----------   ----------  ----------  ----------  ----------

 1800         0           80          90          90

 5000         0           80          90          90









  POINT NUMBER :   1
  SCREEN  1  OF  1
                                                          <Esc> exit screen
```

Figure C4. Sample landside geometry data input.

FILE DATACHK3: Three-Layer Model

```
          *********     LEVEEMSU     *********
                   LEVEE UNDERSEEPAGE
        *********     v 2.1 JAN 94      *********
---------------------------------------------------------------------

              To Select Menus Use:  → arrow keys

|        INPUT          |CALCULATIONS| DISPLAY  |  OUTPUT/  |  SYSTEM  |
| 2 - LAYER | 3 - LAYER |            |  DATA    |  RESULTS  |          |

              @@@@

Options:
       Build (new 3-layer)        <<<  to select option
       Read (from disk)                enter Highlighted letter
       Write (to disk)
       Edit (3-layer data)
       Print (3-layer data)
```

Figure C5. 3-Layer selection menu.

```
           |   CONTROL MENU FOR DATA INPUT   |    ↑y
                                                  |
                                                  └──→x
MAIN TITLE Three-Layer Model          SUB TITLE  Test Problem

HORIZONTAL PERMEABILITY PERVIOUS SUBSTRATUM .2

        RIVERSIDE DATA                       LANDSIDE DATA
        --------------                       --------------
MID LAYER HORIZ PERM   .0002          MID LAYER HORIZ PERM   .0002

MID LAYER VERT PERM    .0002          MID LAYER VERT PERM    .0002

NUMBER OF SECTIONS     2              NUMBER OF SECTIONS     2

PERM CALC METHOD       const          PERM CALC METHOD       const

TOP BLANKET VERT PERM .0002           TOP BLANKET VERT PERM .0002

WATER ELEV             110            WELL PRESENT   no
                                                    <Esc> exit screen
```

Figure C6. Sample control menu input.

RIVERSIDE GEOMETRY DATA INPUT SCREEN

↑y
└──→x

X	Y1	Y2	Y3	Y4
0	0	70	80	90
1500	0	70	80	90

POINT NUMBER : 1
SCREEN 1 OF 1

<Esc> exit screen

Figure C7. Sample riverside geomery data input.

LANDSIDE GEOMETRY DATA INPUT SCREEN

↑y
└──→x

X	Y1	Y2	Y3	Y4	YWATER
1800	0	70	80	90	90
5000	0	70	80	90	90

POINT NUMBER : 1
SCREEN 1 OF 1

<Esc> exit screen

Figure C8. Sample landside geometry data input.

Listed Input File: Two-Layer Model

irregular foundation
test problem

KF = .2
PERMFLAGR = const PERMRIV = .0002
PERMFLAGL = const PERMLAND = .0002

xx	yy1	yy2	yy3	yywater	d	z	kb
0.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
500.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
700.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
900.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1000.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1100.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1200.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1250.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1300.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1350.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1400.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1425.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1450.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1475.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1500.00	0.00	80.00	90.00	110.00	80.0	10.0	0.00020
1525.00	0.00	80.00	90.00	108.33	80.0	10.0	0.00000
1550.00	0.00	80.00	90.00	106.67	80.0	10.0	0.00000
1575.00	0.00	80.00	90.00	105.00	80.0	10.0	0.00000
1600.00	0.00	80.00	90.00	103.33	80.0	10.0	0.00000
1625.00	0.00	80.00	90.00	101.67	80.0	10.0	0.00000
1650.00	0.00	80.00	90.00	100.00	80.0	10.0	0.00000
1675.00	0.00	80.00	90.00	98.33	80.0	10.0	0.00000
1700.00	0.00	80.00	90.00	96.67	80.0	10.0	0.00000
1725.00	0.00	80.00	90.00	95.00	80.0	10.0	0.00000
1750.00	0.00	80.00	90.00	93.33	80.0	10.0	0.00000
1775.00	0.00	80.00	90.00	91.67	80.0	10.0	0.00000
1800.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1850.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1875.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1900.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1925.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1950.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
1975.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2000.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2025.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2050.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2075.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2100.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2125.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2225.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2325.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2425.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2625.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
2825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020

Output File: Two-Layer Model (Concluded)

3325.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
3825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
4325.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
4825.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020
5000.00	0.00	80.00	90.00	90.00	80.0	10.0	0.00020

xx	piezel	reshead	z	i
0.00	110.00	0.00	10.00	0.0000
500.00	108.35	-1.65	10.00	-0.1651
700.00	107.44	-2.56	10.00	-0.2558
900.00	106.41	-3.59	10.00	-0.3594
1000.00	105.82	-4.18	10.00	-0.4180
1100.00	105.18	-4.82	10.00	-0.4817
1200.00	104.48	-5.52	10.00	-0.5516
1250.00	104.11	-5.89	10.00	-0.5891
1300.00	103.72	-6.28	10.00	-0.6284
1350.00	103.30	-6.70	10.00	-0.6697
1400.00	102.87	-7.13	10.00	-0.7132
1425.00	102.64	-7.36	10.00	-0.7358
1450.00	102.41	-7.59	10.00	-0.7589
1475.00	102.17	-7.83	10.00	-0.7827
1500.00	101.93	-8.07	10.00	-0.8071
1525.00	101.68	-6.65	10.00	-0.6652
1550.00	101.43	-5.23	10.00	-0.5233
1575.00	101.19	-3.81	10.00	-0.3814
1600.00	100.94	-2.40	10.00	-0.2395
1625.00	100.69	-0.98	10.00	-0.0977
1650.00	100.44	0.44	10.00	0.0441
1675.00	100.19	1.86	10.00	0.1859
1700.00	99.94	3.28	10.00	0.3277
1725.00	99.70	4.70	10.00	0.4695
1750.00	99.45	6.11	10.00	0.6113
1775.00	99.20	7.53	10.00	0.7530
1800.00	98.95	8.95	10.00	0.8947
1825.00	98.70	8.70	10.00	0.8701
1850.00	98.46	8.46	10.00	0.8461
1875.00	98.23	8.23	10.00	0.8228
1900.00	98.00	8.00	10.00	0.8001
1925.00	97.78	7.78	10.00	0.7780
1950.00	97.56	7.56	10.00	0.7565
1975.00	97.36	7.36	10.00	0.7355
2000.00	97.15	7.15	10.00	0.7151
2025.00	96.95	6.95	10.00	0.6953
2050.00	96.76	6.76	10.00	0.6760
2075.00	96.57	6.57	10.00	0.6572
2100.00	96.39	6.39	10.00	0.6389
2125.00	96.21	6.21	10.00	0.6211
2225.00	95.55	5.55	10.00	0.5545
2325.00	94.95	4.95	10.00	0.4950
2425.00	94.42	4.42	10.00	0.4416
2625.00	93.51	3.51	10.00	0.3513
2825.00	92.79	2.79	10.00	0.2786
3325.00	91.58	1.58	10.00	0.1578
3825.00	90.86	0.86	10.00	0.0862
4325.00	90.42	0.42	10.00	0.0417
4825.00	90.10	0.10	10.00	0.0101
5000.00	90.00	0.00	10.00	0.0000

Listed Input File: Three-Layer Model

```
Three-Layer Model
Test Problem

KF =  .2
PERMFLAGR = const    PERMRIV  =  .0002
PERMFLAGL = const    PERMLAND =  .0002
kmhr      =  .0002          kmvr     =  .0002
kmhl      =  .0002          kmvl     =  .0002
```

xx	yy1	yy2	yy3	yy4	yywater	d	z2	z1	kb
0.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
500.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
700.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
900.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1000.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1100.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1200.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1250.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1300.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1350.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1400.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1425.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1450.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1475.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1500.00	0.00	70.00	80.00	90.00	110.00	70.0	10.0	10.0	0.00020
1525.00	0.00	70.00	80.00	90.00	108.33	70.0	10.0	10.0	0.00000
1550.00	0.00	70.00	80.00	90.00	106.67	70.0	10.0	10.0	0.00000
1575.00	0.00	70.00	80.00	90.00	105.00	70.0	10.0	10.0	0.00000
1600.00	0.00	70.00	80.00	90.00	103.33	70.0	10.0	10.0	0.00000
1625.00	0.00	70.00	80.00	90.00	101.67	70.0	10.0	10.0	0.00000
1650.00	0.00	70.00	80.00	90.00	100.00	70.0	10.0	10.0	0.00000
1675.00	0.00	70.00	80.00	90.00	98.33	70.0	10.0	10.0	0.00000
1700.00	0.00	70.00	80.00	90.00	96.67	70.0	10.0	10.0	0.00000
1725.00	0.00	70.00	80.00	90.00	95.00	70.0	10.0	10.0	0.00000
1750.00	0.00	70.00	80.00	90.00	93.33	70.0	10.0	10.0	0.00000
1775.00	0.00	70.00	80.00	90.00	91.67	70.0	10.0	10.0	0.00000
1800.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
1825.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
1850.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
1875.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
1900.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
1925.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
1975.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2025.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2075.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2125.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2225.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2325.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2425.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2625.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
2825.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
3325.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
3825.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020

4325.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
4825.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020
5000.00	0.00	70.00	80.00	90.00	90.00	70.0	10.0	10.0	0.00020

xx	piezelt	piezelb	deltheadt	deltheadb	z1	z2	itop	ibot
0.00	110.00	110.00	0.00	0.00	10.00	10.000	0.000	0.0000
500.00	108.98	107.97	-1.02	-1.02	10.00	10.000	-0.102	-0.1017
700.00	108.49	106.98	-1.51	-1.51	10.00	10.000	-0.151	-0.1511
900.00	107.95	105.90	-2.05	-2.05	10.00	10.000	-0.205	-0.2048
1000.00	107.66	105.32	-2.34	-2.34	10.00	10.000	-0.234	-0.2338
1100.00	107.35	104.71	-2.65	-2.65	10.00	10.000	-0.265	-0.2645
1200.00	107.03	104.06	-2.97	-2.97	10.00	10.000	-0.297	-0.2971
1250.00	106.86	103.72	-3.14	-3.14	10.00	10.000	-0.314	-0.3142
1300.00	106.68	103.36	-3.32	-3.32	10.00	10.000	-0.332	-0.3318
1350.00	106.50	103.00	-3.50	-3.50	10.00	10.000	-0.350	-0.3500
1400.00	106.31	102.62	-3.69	-3.69	10.00	10.000	-0.369	-0.3689
1425.00	106.21	102.43	-3.79	-3.79	10.00	10.000	-0.379	-0.3785
1450.00	106.11	102.23	-3.89	-3.88	10.00	10.000	-0.389	-0.3881
1475.00	105.97	102.03	-4.03	-3.93	10.00	10.000	-0.403	-0.3934
1500.00	104.59	101.83	-5.41	-2.76	10.00	10.000	-0.541	-0.2759
1525.00	103.89	101.63	-4.44	-2.27	10.00	10.000	-0.444	-0.2265
1550.00	103.19	101.42	-3.48	-1.77	10.00	10.000	-0.348	-0.1771
1575.00	102.49	101.22	-2.51	-1.28	10.00	10.000	-0.251	-0.1277
1600.00	101.79	101.01	-1.54	-0.78	10.00	10.000	-0.154	-0.0783
1625.00	101.10	100.81	-0.57	-0.29	10.00	10.000	-0.057	-0.0288
1650.00	100.40	100.60	0.40	0.21	10.00	10.000	0.040	0.0206
1675.00	99.70	100.40	1.36	0.70	10.00	10.000	0.136	0.0700
1700.00	99.00	100.19	2.33	1.19	10.00	10.000	0.233	0.1195
1725.00	98.30	99.99	3.30	1.69	10.00	10.000	0.330	0.1689
1750.00	97.60	99.79	4.27	2.18	10.00	10.000	0.427	0.2184
1775.00	96.91	99.58	5.24	2.68	10.00	10.000	0.524	0.2679
1800.00	96.21	99.38	6.21	3.17	10.00	10.000	0.621	0.3173
1825.00	94.65	99.18	4.65	4.53	10.00	10.000	0.465	0.4534
1850.00	94.49	98.99	4.49	4.49	10.00	10.000	0.449	0.4491
1875.00	94.40	98.79	4.40	4.40	10.00	10.000	0.440	0.4397
1900.00	94.30	98.61	4.30	4.30	10.00	10.000	0.430	0.4303
1925.00	94.21	98.42	4.21	4.21	10.00	10.000	0.421	0.4212
1975.00	94.03	98.07	4.03	4.03	10.00	10.000	0.403	0.4034
2025.00	93.86	97.73	3.86	3.86	10.00	10.000	0.386	0.3864
2075.00	93.70	97.40	3.70	3.70	10.00	10.000	0.370	0.3700
2125.00	93.54	97.09	3.54	3.54	10.00	10.000	0.354	0.3544
2225.00	93.25	96.50	3.25	3.25	10.00	10.000	0.325	0.3249
2325.00	92.98	95.96	2.98	2.98	10.00	10.000	0.298	0.2976
2425.00	92.73	95.46	2.73	2.73	10.00	10.000	0.273	0.2729
2625.00	92.29	94.58	2.29	2.29	10.00	10.000	0.229	0.2288
2825.00	91.91	93.83	1.91	1.91	10.00	10.000	0.191	0.1913
3325.00	91.21	92.43	1.21	1.21	10.00	10.000	0.121	0.1213
3825.00	90.73	91.46	0.73	0.73	10.00	10.000	0.073	0.0731
4325.00	90.38	90.76	0.38	0.38	10.00	10.000	0.038	0.0379
4825.00	90.09	90.19	0.09	0.09	10.00	10.000	0.009	0.0095
5000.00	90.00	90.00	0.00	0.00	10.00	10.000	0.000	0.0000

Appendix D
Example Data Files

The listings of data files used for the parameter analysis and case studies presented in this report follow. Working from these files, the user performed the analyses by systematically altering the input file.

DATACHK models a levee section amenable to conventional analyses. It has a 10-ft-thick top blanket overlying an 80-ft-thick pervious substratum. An example is listed below:

```
IRREGULAR FOUNDATION
TEST PROBLEM
.2000
2 "CONST" .0002 110
0 0 80 90
1550 0 80 90
2 "CONST" .0002
1800 0 80 90 90
5000 0 80 90 90
NO WELL
```

DATACHK3 models a levee section with three-layer foundation. It has a 10-ft-thick top blanket overlying a 10-ft-thick middle layer and a 70-ft-thick pervious substratum. An example is listed below:

```
THREE-LAYER MODEL
TEST PROBLEM
.2000
0.0002 0.0002
2 "CONST" .0002 110
0 0 70 80 90
1500 0 70 80 90
0.0002 0.0002
2 "CONST" .0002
1800 0 70 80 90 90
5000 0 70 80 90 90
NO WELL
```

File DATADCH models a levee section with a 15-ft-thick top blanket and a landside ditch. It is listed below:

```
TEST FILE "DATADCH"
DITCH 1V ON 3H  200 FT FROM LEVEE  10 FT DEEP
200
2 "CONST" .0003 100
0 0 65 80
2000 0 65 80
6 "CONST" .0003
2200 0 65 80 80
2400 0 65 80 80
2430 0 65 70 80
2440 0 65 70 80
2470 0 65 80 80
7000 0 65 80 80
NO WELLS
```

File DATAWELL is similar to file DATACHK with the exception that a line of relief wells is molded at the levee toe. It is also listed below:

```
IRREGULAR FOUNDATION
TEST PROBLEM
0.2000
2 "CONST" 0.0002 110
0 0 80 90
1500 0 80 90
2 "CONST" 0.0002
1800 0 80 90 90
5000 0 80 90 90
WELL
1820 94
```

File MAGN.dat include the input data for the case study of Magnolia Levee. Variation in the length of the riverside and landside blankets were induced to conduct the analysis. The idealized section consists of 7-ft-thick clay blanket underlain by 100-ft-thick pervious foundation.

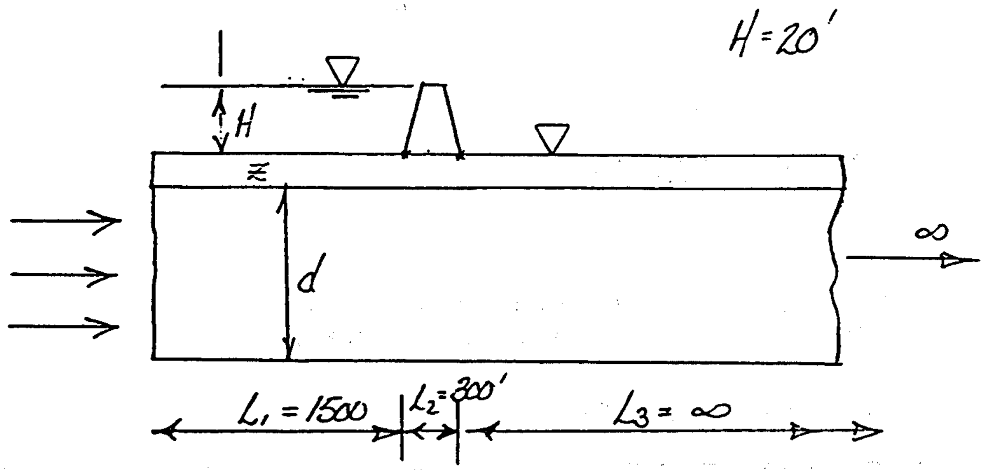
```
MAGNOLIA LEVEE - OHIO
CASE STUDY
.02
3 "CONST" .0002 950.1
0 841.2 941.2 948.2
2000 841.2 941.2 948.2
2016 841.2 941.2 950.0
3 "CONST" .0002
2156 841.2 941.2 950.0 950.0
2172 841.2 941.2 948.2 948.2
```

```
2347 841.2 941.2 948.2 948.2
NO WELL
```

File SNY.dat include the input data for the case study of Sny Island Levee. This site was characterized by three-layer irregular foundation. This analysis section characterizes the soil profile at piezometer range "F." Pool elevations on the riverside were varied in the analysis to simulate recorded storm events.

```
SNY ISLAND - RANGE F
CASE STUDY-7/13/92
0.2000
0.01 0.04
7 "CONST" .0002 463.67
0 423.5 451.5 453.5 453.5
120 423.5 451.5 453.5 459
275 423.5 451.5 453.5 457.5
300 423.5 451.5 453.5 455.5
335 423.5 451.6 453.6 455.5
360 423.5 451.7 453.7 457
470 423.5 454.5 456.5 459
0.0002 0.0002
5 "CONST" .0002
680 423.5 451.5 454.5 459.5 459.5
720 423.5 451 453 457 457
760 423.5 451 453 455.5 455.5
900 423.5 450.5 452.5 456.5 456.5
1080 423.5 450.5 452.5 456.5 456.5
NO WELL
```

Appendix E
Hand Check, File DATACHK



$H = 20'$	$L_1 = 1500'$	$k_f/k_b = 1000$
$z = 10'$	$L_2 = 300'$	
$d = 80$	$L_3 = \infty$	

$$C_r = \sqrt{\frac{k_{br}}{k_f \cdot z \cdot d}} = \sqrt{\frac{(1)}{1000 \cdot 10 \cdot 80}} = 0.001118033$$

same for riverside and landside

$$x_3 = \frac{1}{c} = 894.43'$$

$$x_1 = \frac{\tanh(cL_1)}{c} = \frac{\tanh(.001118033 \times 1500)}{0.001118033}$$

x_1 = 834.03′

$$h_o = \frac{Hx_3}{x_1 + L_2 + x_3} = \frac{(20)(894.43)}{834.03 + 300 + 894.43} = 8.819'$$

Rework using open exit @ L_3 = 3000′ (modeled problem).

$$x_3 = \frac{\tanh(c \cdot L_3)}{c} = \frac{\tanh(.001118033 \times 3000)}{.001118033} = 892.25$$

$$h_o = \frac{(20)(892.25)}{834.03 + 300 + 894.03} = 8.799$$

Calculated gradient: Theoretical problem 0.882
(z - 10′) Modeled problem 0.880

Landside Heads: ($L_3 = \infty$)

x computer	x landside	$h_x = h_o e^{-cx}$	Computer
1800	0	8.819′	8.862
2000	200	7.052′	7.075
2250	450	5.332	5.332
2450	650	4.264	4.245
2700	900	3.048	3.193
2950	1150	2.438	2.391
3450	1650	1.394	1.346
3950	2150	.797	.723
4450	2650	.456	.325

Landside Heads (L_3 = 3000)

$$h_x = h_o \frac{\sinh c(L_3-x)}{\sinh cL_3} = \frac{8.819 \sinh [.001118033(3000-x)]}{\sinh (.001118033 \times 3000)}$$

$$= 0.6170398 \sinh [.001113033(3000-x)]$$

x computer	x landside	h_x
1800	0	8.819
2000	200	7.047
2250	450	5.321
2450	650	4.247
2700	900	3.199
2950	1150	2.402
3450	1650	1.327
3950	2150	.679
4450	2650	.248

Appendix F
Notation

A	Cross-sectional area normal to the flow
d	Uniform thickness of pervious substratum
D	Thickness of pervious substratum at a given node
h_o	Residual head at levee toe
h_x	Residual head at distance x from landside toe levee (see Figure 3)
H	Net head on levee (see Figure 3)
H_{av}	Average head in a line of wells
i	Hydraulic gradient
k	Soil coefficient of permeability
k_b	Permeability of top blanket
k_{bl}	Permeability of landside top blanket
k_{br}	Permeability of riverside top blanket
k_f	Permeability of pervious substratum
kmv	Vertical permeability of the middle layer
kmh	Horizontal permeability of the middle layer
L_1	Distance from open seepage entrance to riverside levee toe
L_2	Distance from riverside levee toe to landside levee toe

L_3	Distance from landside levee toe to open exit
msl	Mean sea level
NGVD	National Geodetic Vertical Datum
Piezelbot	Piezometric head on the bottom of the middle layer
Piezeltop	Piezometric head on the top of the middle layer
Q	Quantity of flow
Qwell	Flow to well line
x_3	Distance from landside levee toe to effective seepage exit
z1	Thickness of top blanket
z2	Thickness of middle layer

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1995	Final report

4. TITLE AND SUBTITLE
LEVEEMSU: Analysis Software for Levee Underseepage and Rehabilitation

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
See reverse.

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report GL-95-9

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The computer program LEVEEMSU for analysis of levee underseepage is presented. Analysis algorithms implemented in LEVEEMSU are based on numerical modeling of the flow domain, and subsurface geologic conditions can be idealized from two-layer or three-layer representation with a unit length. With the program LEVEEMSU, levee underseepage analyses can be performed while irregular finite and infinite geometry, variable blanket permeability, lines of relief wells, and landside and riverside ditches and borrow pits are considered. In general, parameter studies with application of the analysis model to problems with ditches and relief wells indicated that the program exhibits consistent behavior. Magnolia Levee, located in Huntington District, and Sny Island Levee, located in Rock Island District, were selected as case studies to demonstrate the application of the two-layer and three-layer models, respectively. Results of the case studies emphasized the importance of accurate characterization of the foundation sublayers. LEVEEMSU provides a convenient analysis tool that should allow designs to approximately model actual field conditions. However, flood protection is a complex system involving design, construction, maintenance, and performance evaluation of levees. The use of LEVEEMSU can provide flexibility in exploring the influence of varying key analysis parameters on the predicted results. Such a flexibility can lead to reevaluation of design criteria with the benefit of reducing cost and improved safety.

14. SUBJECT TERMS

Case studies	Remedial measures
Finite difference	Underseepage
Levees	

15. NUMBER OF PAGES
119

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

7. (Concluded).

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